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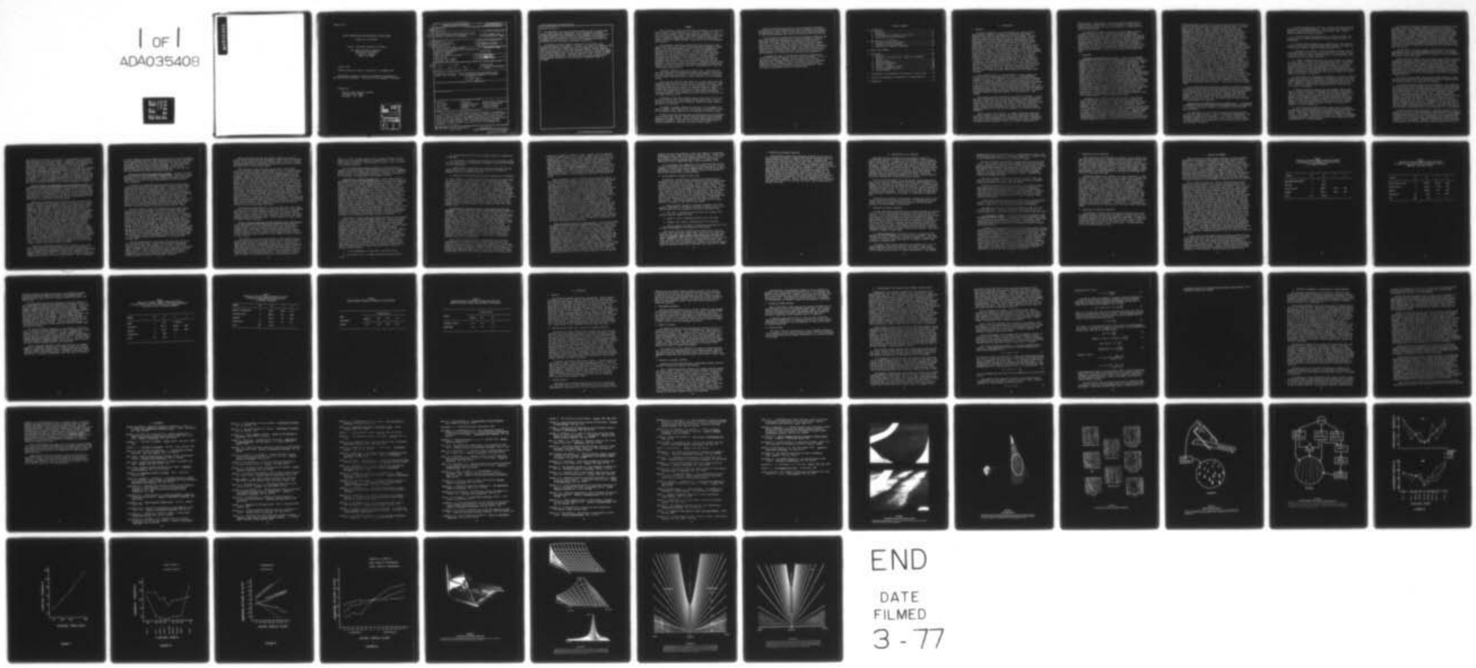

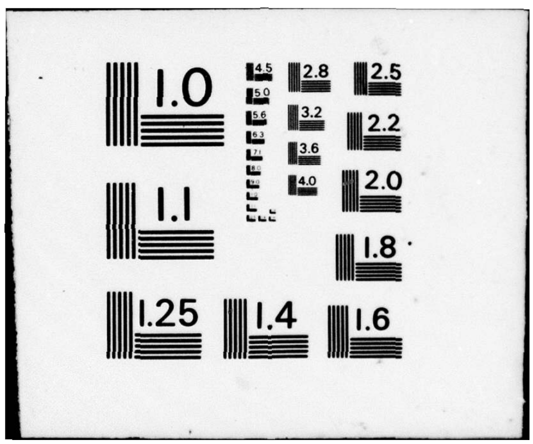
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Report 1977-1

SPATIAL ORIENTATION FROM HIGH-VELOCITY BLUR PATTERNS:

Perception of Divergence

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Under conditions of high-velocity motion the textures in an observer's field of view are transformed into "blur patterns," patterns of "blur lines" formed by elements in the terrain appearing to streak as a result of the visual system's persistence. Under these conditions most of the usual visual correlates of depth perception fail to operate but new motion-related information becomes available in the form of blur-line divergence and curvature. → next page

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The experiments reported here determine human ability to process this rapidly moving divergence information. Using simulated blur patterns, divergence thresholds were determined for nine segments of the visual field at three velocities; observers were also required to use the divergence information for orientation of a surface in correspondence with their own perceptions of the inclination of the plane of motion.

As patterns are moved forward the periphery of the visual field divergence thresholds rise steadily. Changes in the number of elements in the display, the velocity of element motion or the method of display (natural multiply-varying stimuli versus pure-divergence stimuli) did not appreciably alter these threshold values and this may be of particular interest in remote piloted display applications. Observers differed in their ability to orient using the given information. The implications for motion simulation and moving-observer orientation are discussed and a mathematical model is included.

SUMMARY

Under conditions of high-velocity motion the textures in an observer's field of view are transformed into "blur patterns," patterns of "blur lines formed by elements in the terrain appearing to streak as a result of the visual system's persistence. Under these conditions most of the usual visual correlates of depth perception fail to operate but new motion-related information becomes available in the form of blur-line divergence and curvature.

The experiments reported here demonstrated the sensitivity of the human visual system to the rapidly-moving divergence information in these patterns and also demonstrated successful use of that information for surface orientation by human observers. Divergence thresholds were determined for nine locations in the visual field at three velocities; observers also used the divergence information to orient a surface to correspond with the degree of slant displayed in the blur patterns. Divergence was defined here in terms of the display itself; that is, divergence angle was defined as the angle between the right and left outermost lines possible in any given display. Divergence thresholds were measured in terms of the smallest divergence angle observers were able to recognize as differing from zero where zero corresponded to all the lines in the display being parallel.

Individual differences were great on these tasks. Those observers with lower thresholds for divergence judgments also tended to be the ones who could orient more successfully, and it is believed that a test based on blur pattern perception might be a useful adjunct to a pilot screening battery.

Having the blur pattern in the center of his visual field allows the observer to make the most efficient use of blur pattern information. Mean divergence thresholds for a central fixation point were 3.2°, suggesting a relatively high level of sensitivity. When the display is viewed further toward the periphery of the visual field, sensitivity drops but it is still high enough for blur patterns to provide useful information. Divergence threshold values around the fovea 20° out are 5.1°, 40° out are 7.1°, and 75° out are 11.8°.

Performance at the three different angular velocities of 20, 40, and 80°/sec was equally good. This suggests the possibility that it may be possible to simulate or display directional information without regard to the velocity of the craft.

The number of elements composing the display, 16 or 32 elements for each 5" diameter video display frame, did not make any difference in terms of the threshold values obtained or in the observer's ability to orient.

Stimuli created by electronic means and employing only pure divergence did not differ from "natural" stimuli created by optical means and having gradients of element velocity, element size and element density existing along with divergence. Again this result might permit simplification of display parameters for simulation and remote piloted displays.

Observers demonstrated an ability to use blur pattern information successfully for surface orientation but they also demonstrated a tendency to underestimate surface slant, a factor which might require exaggeration of some display parameters when these are planned for simulation purposes.

Practice greatly increased sensitivity to divergence information, and this would suggest the desirability of supplying training to those who might need blur pattern information when operating under difficult conditions. The human sensitivity to blur pattern information suggest that continuous blur patterns, now lacking in discrete-frame video or motion picture displays, might be necessary for optimal motion information transmission in some high-velocity cases. Also, artificial texturing on landing surfaces, especially under difficult visibility conditions as in Artic whiteouts or in difficult carrier landings could be beneficial.

A mathematical model is included which provides a foundation for relating blur pattern information to actual craft orientation. This is a new areas of perception, however, and its complexity is stressed. Additional work is needed to explore the areas of curvature, divergence chance and curvature change, as well as the effect on blur pattern perception of having fixed reference lines to aid processing. Some of this work is now underway and will be reported later.

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A. Introduction

1. Objective

The usual conceptions of visual orientation by a moving observer regard textural elements as though they provided the same visual stimulation that they do under conditions of static viewing. Actually texture in motion may lose many of its static characteristics but it gains important new motion-related parameters which emerge as direct consequences of the motion itself and the nature of the visual system. Specifically, points of light and dark in the "static" domain are transformed into streaks called motion bands or blur lines in the motion domain because of persistence in the visual system. A stationary line, to the visual system, is a simultaneously-stimulated row of retinal points but because of temporal "slack" in the photoreceptors and in the succeeding neural elements and their interconnnections, there is a great deal of tolerance in how simultaneous the stimulation must be. As a result, a single point of light or dark moving across the retina can stimulate successive locations quickly enough together that the visual impression is given of a line dragging along behind the point. The length of this line depends on the velocity of the point, its intensity, contrast, hue, context, state of dark adaptation of the eye, etc. The slope of this blur line will of course depend on the direction of movement of the point on the retina. Doubtless such a blur line excites the slope-sensitive cortical units of Hubel and Wiesel (1959, 1965) just as an actual static line does.

Thus a textured field, to a moving observer's visual system, is a field of variously sloped and curved blur lines. The motion-related information in these "blur patterns" is not in terms of motion of textural elements in time per se. Rather, at each separate moment, each blur line in the blur pattern displays the motion history of the element that produced it by virtue of its own characteristic shape and the observer is left processing a sort of time-varying stabilized image of variously curved and diverged stationary "lines." Figure 1 shows some typical naturally-occurring blur patterns photographed from a vehicle moving at high speed. The motion parameters embedded in these photographs will be discussed in a later section.

Blur patterns are not restricted to high-velocity situations. In fact they may be important in all but the very slowest of visual transformations. The work of Smith (1969) and of Brown (1931b) combined with the author's observations indicates that even with angular velocities of motion less than 1°/sec substantial blur patterns can be formed. Thus even at walking speeds a large portion and perhaps all of the visual field may be motion blurred depending on the light-related parameters like contrast and on eye movements.

Motion-produced "blur patterns" are commonly experienced, especially by pilots of rapidly moving vehicles, yet little research has been done until now on human processing of the information they convey. Research on very rapid visual transformations has significance in relation to theories of motion and form perception, as well as in practical applications to

vehicle control. Psychophysical information about fast-motion vision could be used to maximize human visual performance in high-velocity situations and to improve the design of simulators, of motion monitors, and of piloted displays.

Two important blur pattern parameters are the divergence and the curvature of the blur lines. Previous investigations (Harrington dissertation) have shown that human observers are extremely sensitive to disparities of slope and curvature in fields of stationary line elements; the work to be reported here shows that they are also quite sensitive to divergence when it occurs in motion-produced blur patterns and also demonstrates the potential utility of this information. Divergence is defined here in terms of the simulated blur pattern displays used, as the angle between the outermost lines possible in the display (Figure 2) if these were extrapolated to a point off the display at which they would meet.

2. Background

Low-Velocity Transformations as Stimuli. Insofar as the proposed research deals with a new area of visual perception, a survey of several related areas is provided. Optical transformations have recently received attention as sources of information about movement, form and depth. For example, Gibson (1959) was one of the first to state that there is effective stimulus information in the ambient optic array and that transformations, orderly changes of the optic array over time, can serve as stimuli. Gibson (1958, 1966, 1967) has said that perceptual systems respond directly to aspects of overall transformations and to characteristics of the optical array that are invariant during transformation. The percept comes directly from aspects of the transformation itself, critically depending on the timing of object movement and upon other factors that contribute to the overall array, such as changing background and occlusions (Gibson, 1965, 1971, 1973). Gibson has emphasized the importance of change of environmental events as given to the eye by transformations of the optical pattern, as one aspect of the general problem of sensory control of behavior by feedback stimulation, and a number of studies have been done at Cornell and elsewhere (Gibson & Carel, 1952; Gibson, et al., 1959; Gibson & Gibson, 1957; Fieandt & Gibson, 1959; Johansson, 1964) to investigation transformations involved in motion and form perception from this "direct perception" (Gibson, 1972) point of view.

Elsewhere, in an effort to isolate those aspects of low-velocity optical transformations important to perception and to determine the higher-order stimuli that remain invariant amidst change when the corresponding perceptions are invariant, a number of investigations have been conducted. One of the earliest was by Wallach and O'Connell (1953). Their transformations of the proximal array were two-dimensional projections of rotating forms that in fact were seen often as three-dimensional objects in motion. They termed this the kinetic depth effect. Johansson (1964) has searched for the "decoding principles" by which the proximal array transformations are decoded and depth-related perceptions are given. Johansson states that changes in a two-dimensional figure may be perceived as three-dimensional motions of an object with common shape and size and

he has approximately verified this principle by simluating the rotation of straight lines two-dimensionally (Johansson & Jansson, 1968). In another type of study Johansson (1964) asked what proximal information was specifically related to changes in depth, and simulating projected rotations of a rectangle, found ambiguity in the percepts of observers. Sometimes the simulated rotation was seen as a rotation in depth and sometimes as an elastic transformation. When two-dimensional changes involved both the horizontal and the vertical, motion in depth was seen; Johansson hypothesized that there are conditions in which every two-dimensional change in the proximal stimulation is projected out as a motion in depth. (Marmolin [1972] was unable to verify this hypothesis, finding that a fixed proportion of the proximal change is not projected out as motion in the third dimension, but is perceived as a change of size.) Based on further investigations Johansson has developed a model to specify decoding principles. In response to work such as that of Gibson and Johansson and of a large number of investigators studying rotating forms (for example, the trapezoidal window) Braunstein has studied polar and parallel projections of motion (1960, 1962, 1966) and proposed a theory which "accounts for both veridical and illusory perception of direction of rotation of rectangles and trapezoids. The change in angle between horizontal and vertical contours is held to be the principle indicator of direction of rotation with the difference in acceleration in the vertical playing a secondary role" (1972). Again here is an example where transformations of the optical array, for instance angles changing and vertical sides moving according to a specific acceleration function, are being implicated as giving rise to specific perceptions of form and depth. Hofsten (1973) has investigated proximal velocity functions as possibly being super stimuli that give depth information directly in the optic array. He has done so by moving a single dot according to particular velocity functions. In the same vein, Gibson (1950) and Llewellyn et al. (1971) have investigated pure optical expansion or looming as a possible primary stimulus for translatory motion in depth. These results will be discussed later.

It is evident that many investigators, though not necessarily agreeing with Gibson on the immediacy with which percepts are given by transformations in the optical array, have joined enthusiastically in the search for purely optic transformations that are specifically related to form and depth perception. Yet none of these contributions relating depth, form and movement are based on research that employed movement velocities fast enough to produce strong blurring. The sizeable realm of fast-transformation space perception is unexplored.

The Effect of Fast-Transformations on an Optical Array. In formulating a theoretical viewpoint that extends to fast-motion-produced transformations it is necessary to note the changes of transformation rules that rapid motion introduces.

As higher velocities of the retinal image lead to motion-produced blurring, the domain of points, lines and relationships encountered at low velocities is mapped into a new domain. To illustrate, consider the following mappings from the slow-motion domain to the fast-motion domain of certain elements and transformations usually thought to carry significant perceptual information.

1. Points are mapped into "lines" as is evident when one looks from the window of a speeding automobile. Fine textures on the ground such as patches of gravel become blurred into fields of blur lines. Texture gradients become blur pattern gradients.

2. Lines are mapped into motion bands or elongated surfaces. The width of the blur surface depends on the length of the line and on its orientation.

3. Surfaces remain surfaces but are stretched out in the direction of motion, the extent of stretching depending on velocity, the amount and kind of light reflected, state of retinal adaptation, etc.

4. Brightness and velocity of a moving element are mapped into blur line length because a very bright moving object will have a more lasting effect at each retinal locus. (Of course state of dark adaptation, color and other variables are again important.)

5. A shape's dimensions along the direction of motion are distended and are related to lightness of the resulting motion bands. The corners of a shape become blur lines, the sides motion bands. For instance if a triangle were mapped through the transformation caused by blurring one would see three blur lines, corresponding to the corners (unless two corners were moving in line with each other), and a configuration of motion bands, corresponding to the sides with possible over-lapping, that would depend on the figure's orientation.

6. Motion parallax, the apparently differential velocities of objects at different distances from the observer, now begins to involve blur line lengths because the objects themselves will be motion-blurred to an extent that is dependent on their angular velocities relative to the retina. Also, a new kind of motion parallax emerges where blur lines may "move" in relation to one another.

7. Motion perspective, apparent moving of elements along specific paths that depend on direction of movement and distance of the element from the observer, reverts to a situation like the linear perspective one finds in a completely static situation because the apparent paths of movement of the elements become blur lines that converge at the horizon just as railroad tracks and sides of squares do in the static situation. Because of this both the divergence and the curvature in blur patterns become very important potential sources of motion information for an observer, as will be pointed out.

8. Other perceptual information also changes during fast motion. For example, eye-head feedback from muscles, and depth cues involving eye muscle change such as convergence or accomodation change their roles because the elements may be moving too fast for feedback to operate; in the blurring domain it would still be possible for example to accomodate to produce maximally sharp contours of the blur lines themselves and thus form the basis for a distance judgment.

To illustrate the potential consequence of mapping slow-motion visual information into the blur pattern domain, consider the striking way in which processing of one conventional optical transformation changes at blurring speeds. "Looming," the perceived expansion of textural elements about some point as an object nears an observer or as the observer moves toward a surface, has been investigated in detail to determine its use in the guidance of locomotion. It has been found that even young animals respond to a pattern that looms up rapidly (Schiff, Caviness & Gibson, 1962). Gibson (1950) at first speculated that moving observers may employ the center of the expanding pattern as a reference point, moving in such a way that the center of expansion is maintained at the point toward which they wish to move.

Llewellyn (1971) discovered, however, that subjects are not able to determine the center of a slowly-expanding pattern easily. He contended that subjects merely noted the pattern drift caused by off-course movements and moved to nullify this drift.

Gordon and Michael (1965) in an applied context where there is apparent expansion on the ground surface as well as on the frontal plane have also questioned the importance of the center of the expansion pattern. They state that automobile drivers, unable to employ the center of expansion of the visual field for reference, use highway boundaries to the side and they mention that observers may use the locus of moving points on the road ahead that have zero transverse angular velocity as guidance information. This would be the locus of points that appeared to the driver to be coming straight toward him.

In a similar vein, Calvert (1954) has noted that operators of moving vehicles may use peripheral vision to analyze "streamer" information from motion-blurred objects like road signs for guidance.

If the transformation of looming is now regarded as a blur pattern in the high-velocity domain, extending Calvert's speculation, fast motion maps the textural points into blur lines and Gibson's task of finding the center of an expanding pattern of moving textural elements becomes an easy one of finding the origin of a set of radial "lines." Llewellyn's "pattern drift" information now becomes slope-of-"line"-element information in foveally and peripherally seen blur patterns, including Calvert's perceptual streamers, and Gordon and Michael's locus of zero transverse angular velocity becomes the "blur line" on the highway in front of the observer that is pointing directly toward him. Furthermore this blur line will be the only straight-appearing one in the pattern. All of the other lines in the blur pattern on the road ahead will be both curved and be diverging so that they seem to extrapolate to one side or the other side of the observer.

At high velocities then, perception of locomotion parameters would be possible and even facilitated by processing transformations of the curvature, divergence and spacing of blur line patterns rather than the transformation of moving point positions not only in the special case of expansion transformations, but in the case of other transformations of relative textural position such as the apparent "rotational" transformation of texture beside a moving vehicle when the eyes maintain fixation on some point or such as

the translation of patterns to the side of a vehicle when the eyes merely sweep the passing array without fixation. Tentatively, the usefulness of such information has already been shown. Preliminary investigations using motion pictures with dots moving with velocity functions calculated to correspond to movement in various conditions, e.g., fast looming (Harrington & Sprenger, unpublished experiments), have shown that simulated blur pattern divergence and curvature actually do give three dimensional perceptions from two dimensional arrays. Also, the slopes of real blur lines relative to reference edges on an automobile, like the bottom of the side window, were shown to actually be useable as information for guiding an automobile. It was also determined that the blur patterns directly to the front of a speeding automobile quite sensitively indicated changes in the state of motion to observers, e.g., by way of changes in curvature.

The Effectiveness of Eye Movements in Minimizing Motion Blurring. In a slow-motion situation the moving observer will ordinarily use eye movements to help minimize motion blurring. Essentially his fixations allow him to selectively sample information from either a blurred array or from a retinally semi-stationary one, controlling the kind of information that different areas of his retinas see. In order to fit motion blurring into this context it is necessary to know when and why the mechanisms of slow motion perception break down and blurring ensues.

Employing eye movements to help minimize blurring is only minimally effective, especially at high angular velocity (a measure akin to retinal velocity), because a moving observer can only have, under normal circumstances, a single stationary point on his retinal image irrespective of compensatory eye movements. All other points move on the retina. To illustrate, looking forward or backward the moving observer is confronted with a field that expands or converges about some single point (Gibson, 1950a). To the side one sees "motion parallax" of objects proportional to their relative angular velocities (Helmholtz, 1925), and dependent on eye movement (Graham, 1965). Gibson, Olum and Rosenblatt (1955) working in Cartesian coordinates, Gordon and Michaels (1965) using spherical coordinates, and Whiteside and Samuel (1970) arriving at a torroidal coordinate scheme have derived formulae for calculating the angular velocities of different positions surrounding a moving observer. The work of these investigators can be fairly easily interpreted as showing the existence of a locus of non-fixated points that do have zero relative angular velocity at a given movement when an observer maintains fixation on a single moving point, but these points are not stationary in the usual sense. They are merely pausing momentarily to reverse apparent direction, and in the next moment they will accelerate, blur, and new points will pass through the circular (if the eye is at ground level) zero-velocity locus. Of course, when angular velocity of objects relative to the eye exceeds a certain value, blur patterns are formed.

Even though eye movements cannot provide a stationary image in the usual sense, an observer in motion does profit greatly from moving his eyes. Accordingly much research has been devoted to specifying positioning and eye movement pursuit parameters (Ludvigh, 1952; Westheimer, 1954; Rashbass, 1961; Yarbus, 1967). It is evident that the foveal image can be rendered semi-motionless at least for short periods. Since large amounts

of visual information can be buffered and processed after brief "stationary" visual presentations (Sperling, 1960; Averbach & Sperling, 1961; and others), at low observer velocities an image on the retina can provide good visual information about form and slow relative movement. At higher velocities eye movement perhaps could be specially educated to attain partial effectiveness but other modes of processing might have to come into play when eye movements are relatively too slow to keep up.

Failure of Eye Positioning--When Blurring Begins. At high velocities motion blurring is usually regarded in a negative way, insofar as it causes breakdown of visual acuity and contour formation when angular velocities reach the point at which the positioning mechanisms of the eye can no longer compensate.

It has been well documented that the dynamic visual acuity (DVA) of a moving observer decreases as relative angular velocity increases even though the eyes attempt to pursue the target. As Ludvigh (1948, p. 63) says, even when the eye is permitted to move in an effort to follow a moving object, visual acuity deteriorates rapidly with increasing angular velocity of the object. With an observer's eyes pursuing at up to 50°/sec, dynamic and static acuity are similar. Dynamic acuity begins to fail however when either the observer or the object moves at above 50°/sec (Miller & Ludvigh, 1962). According to Hulbert et al. (1958), dynamic and static visual acuity becomes totally separated between 60° and 120°/sec. The acuity of an observer with 20/20 vision falls to 20/200 when the observer is moving relatively at 110°/sec (Ludvigh & Miller, 1958).

The eye is capable of very fast movements and could easily keep up with very high velocity movement. So Miller and Ludvigh (1962) have reasoned that the decline in DVA is due to an inability of the eye-positioning system to accurately match angular velocities well enough to provide a still image on the retina. Thus blurring results. At tracking rates as low as 20°/sec, the eye's angular velocity has been seen to vary sporadically and at 110°/sec with the eye attempting "smooth pursuit," velocities of 250°/sec can be seen. It is known that the eye could keep up well enough to a moving object for, on 40° movements during voluntary changes in fixation angular velocities of 400°/sec have been measured. For 90° shifts velocities can approach 1000°/sec (Haber & Hershenson, 1973), and the average velocity of small movements has been estimated at between 100-200°/sec (Miller & Ludvigh, 1962). Neither is the DVA decrement likely due to errors of the positioning mechanisms that center the target image off fovea because off-fovea measurements of static acuity have shown that a 2° displacement produces an acuity decrement to only about 20/25 (Ludvigh, 1949).

Practical demonstrations of the decay of DVA have been carried out that substantiate the above. Subjects have made acuity measurements riding in cars (O'Hara, 1950; Hulbert, et al., 1961), in low flying aircraft (Goodson & Miller, 1969) and in a linc trainer (Miller & Ludvigh, 1962). The latter study, also referred to above, in which the linc was allowed to spin for one minute to allow the effects of angular acceleration to settle out, showed that under these conditions it is immaterial whether the object or the observer is moving.

When one considers that the eye tracking a target in an array is usually subject to vibration due to movement, it would seem to be deprived of even its one theoretical stationary retinal point. Miller and Ludvigh (1962) speculate that as acceleration and the higher derivatives of motion are added, DVA will suffer more and more.

That the visual system often does not and cannot offset angular velocity is evident to anyone riding at 60mph in a car. If dynamic visual acuity begins to break down at about 50°/sec, objects only 50 or 60 feet to the side begin to be blurred in spite of attempted compensatory eye movements. Objects 25-30 feet distant to the side according to the data of Ludvigh and Miller (1958) would be seen foveally with an acuity of 20/200. When one considers objects closer than this at the given velocity normal vision is virtually useless, although excellent blur patterns are formed that could be used for improving guidance of locomotion. Realizing that fixation is usually more to the front without gross compensatory eye movements to the side, blurring at the side is extreme. Peripheral vision lacks acuity, but not necessarily the ability to process aspects of blur line motion. The motion thresholds in the periphery are considerably less than the acuity thresholds and some kinds of motion detection are far more acute peripherally. The work of Ludvigh on the effects of lighting on dynamic visual acuity shows that acuity for moving objects suffers even more than for stationary objects when illumination is diminished. Incorporating these facts with Dodge's (1903) observation that it takes the eye 0.2 sec to react and move shows that for an observer in motion the limits of non-blurred vision are surprisingly restrictive.

The point being emphasized here is not simply that the retinal image is nearly always blurred by motion, for there are ways that a visual system might position the eye and coordinate sampling or even process blurring out within limits. Rather the point is that there are angular velocities commonly experienced where very severe perceptual blurring does take place but where useable blur patterns exist. So far research has always stopped just short of these velocities.

Failure of Contour Mechanisms and the Formation of Blur Line Contours. In the areas around a moving observer where angular velocity causes contour perception to be lost, potentially useful blur contours emerge. Cheatham (1952), employing a masking technique, showed that contour formation takes on the order of 30-100 milliseconds and there is recent evidence stemming from work on dynamic contour perception (DCP) (Smith & Gullick, 1956) that clear contours fail to be formed at angular velocities as low as 14°/sec.

The perception of visual contours begins to suffer probably because the positioning mechanisms of the eye are not able to afford the retina a stable enough image for a long enough period of time. Recent work by Smith and Gullick (1956) elaborating an observation by Michotte (1946) has shown that the contours of a 0.5° black parallelogram moving across a 5° white field begin to blur at about 14°/sec (but if the square is seen to be stationary at the beginning and at the end of its excursion, then its contours remain clear at higher velocities). Smith and Gullick present data collected by increasing stationary pre- and post-exposure time to

300msec. At this value the angular velocity at which contours could be seen clearly had increased (linearly) to around 24°/sec. This is a very modest angular velocity for vision to begin to falter in view of the facts in the preceding section.

Yet even though normal contour perception of a moving observer is impaired, as relative angular velocity increases blur lines will lengthen, forming a new kind of contour, the "contours" of the blur lines themselves. Retinal velocity, which diminishes conventional processing, may prove to be an asset when the needed work on blur patterns is done.

Characteristics of Motion-Produced Blurs. A full understanding of blur patterns requires the consideration of individual blur line formation. Motion blurring occurs because the photochemical and the neural effects of visual stimulation do not stop immediately when the stimulus is removed. Perceptually stimulation of the visual system seems to linger and to reverberate. If a stationary point of light is briefly presented to the retina the corresponding perception of a trained observer is not simply a momentary flash, but rather a series of pulses of varying durations and brightnesses (McDougal, 1904-05). Similarly, when an image is moved smoothly across the retina successively stimulating a sequence of points, observers see these pulses, possibly interacting with effects of the movement itself, as a series of blurred duplicate images seeming to move along behind the original, following by a distance that is dependent on the speed of movement, according to McDougal. The most immediate of these images or pulses (Graham, 1934) are the so-called Charpentier's bands. According to Graham's summary of the appearance of the moving image, slower alterations (of brightness) succeeding the bands, comprise a series of positive afterimages of which the most prominent, the Purkinje afterimage, is absent or very faint in the center of vision, as would be expected according to the explanation that these are due to rod action.

These reports of ghost images were obtained typically by the technique of rotating a disc containing a lighted radial slit. Actually observers in motion or observers of moving targets often fail to notice the ghost images following the target, especially at high velocities where these phantom images trail behind the target at long distances. The more typical response from untrained moving observers, for example automobile passengers, suggests that only streaks or "blur lines" are seen. This is substantiated by experimental observations. Segner, D'Arcy, and Cavallo (quoted in Helmholtz, 1925), probably among the first to investigate motion-produced blurring, whirled a glowing coal in a circle, noting the fiery trail that followed it. DeSilva's (1929) account is representative of the reports of other workers that followed. DeSilva employed a laterally moving slit of light and, excluding pursuit movements of the eyes, noted the effects on perception of the slit at different angular velocities as low as 10°/sec, for instance, Charpentier's bands and the other brightness pulses are already seen travelling well behind the stimulus. DeSilva states:

1. In the neighborhood of 3°/sec there is distinct contour.

2. By the time 10°/sec is reached the outlines become slightly blurry.

3. In the range from 14-21°/sec the object acquires a luminous tail or afterglow.

4. As velocity is increased from 21-58°/sec the tail becomes a sheet of light, unrolling at the beginning of the object's excursion and rolling up at its termination.

5. When velocity is increased from 58-116°/sec the sheet fills the whole excursion and is somewhat vibratory, showing the direction of movement (DeSilva's excursion was 2.7 cm).

6. Above about 116°/sec the sheet becomes stationary in all respects.

J.F. Brown (1931a) has similarly described the appearance of a black patch on a white ground as angular velocity is increased, noting backward apparent movement in certain velocity ranges. Vivianne Smith (1969) has recently measured velocity thresholds for DeSilva's later phases where bands of motion are seen and has found that higher velocities are required for circular "movement bands" if the arc length is increased or luminance is increased and she has found that the response in white light for a 10" target (considerably larger than we shall be using) at 5.7° from the fovea is determined by a scotopic mechanism at all luminances and at 3.3° from the fovea by a scotopic mechanism at low luminances and a photopic mechanism at high luminances, emphasizing the importance of retinal locus to blur pattern perception. At very high velocities invisibility sets in, the critical velocity depending on the target's angular velocity, on state of adaptation and on relative intensity of the target (von den Brink, 1957; Pollock, 1953).

<u>The Physiological Relation of Static Line Perception to Blur Line Perception</u>. A later section will report on human sensitivity to slope and curvature. One would expect the visual system to be sensitive to the parameters of blur patterns relating to slope and curvature because static line elements and blur lines have much in common from a neurophysiological point of view. Hubel and Wiesel (1959, 1965) recording from cats and monkeys and Marg, Adams and Rutlins (1968) recording from humans and many others have discovered "form analysers" in the brain, for example, single neural units that respond to moving bars of particular slope, and Spinelli (1966) finds line and edge detectors in the cat's retina. The movement of these stimuli likely simply serves to overcome the rapidly adapting nature of these units by moving across areas of different sensitivity on the lower-order receptive fields that make up these "slope" units (see Scobey & Harringtion, 1973). Thus, as far as the retina is concerned, a narrow bar or an edge are simply regions of <u>simultaneous</u> activity that lie on a straight line.

For at least two reasons, there is considerable tolerance in how "simultaneous" this activity must be to produce essentially the same effect at higher neural levels. Therefore the response to a line and the response to a rapidly moving point might be expected to be similar. First, neither the retinal photopigments' response nor the resultant generator currents stop immediately when light is removed from the receptor. Evans and Robertson (1965) have found prolonged excitation in the visual cortex

of the cat in response to flashes of light. Second, since the summation of discrete neural impulses is involved at higher levels there will be a temporal grain. Cells at higher levels summating spatially to count the simultaneous effects of the lower-order lined-up units responding to an edge (see Hubel & Wiesel's 1965 model of contour receptors) will also summate the local graded potentials temporally if they are produced by the same inputs excited near-simultaneously by a moving point. It is not meant to suggest that a static line and a blur line will be necessarily indistinguishable, only that they would both excite "line analysers." A theoretical explication of the temporal and spatial summative properties of the visual system in a similar context is available in von den Brink (1957).

Since blur patterns contain information about direction of motion, if blur lines excite form analysers, as was described, a visual system could use its form analysers to analyze the direction-of-motion information inherent in blur pattern slope and curvature changes. A visual system that employed the same units to serve a dual role would be much more effective for its user. A cat pursuing a fly could use its form analysers for guidance of locomotion using environmental forms with sufficiently low angular retinal velocity, and at the the same time, use these same form analysers to guide locomotion using blur patterns formed by nearer textures of higher angular velocity. Simultaneously, the path of the fly could be extrapolated by treating its streaked image as a line of particular slope to be analysed with slope-sensitive "line" analysers. Of course the foregoing observations are not meant to rule out the importance in vision of direction-selective movement-sensitive units in the visual system, which could serve form and motion-analysing functions, such as those found by Goldberg and Wurtz in the superior colliculus of the behaving monkey (1972), by Maturano and Frank (1963) in the pigeon retina, by Barlow, Hill and Levick(1964) in the rabbit retina, by Michael in the optic nerve fibers (1966, 1968) and superior colliculus (1971, 1972a, 1972b) of the ground squirrel, by Hubel and Wiesel (1959, 1962) in the cat's cortex and by others. These units in general seem to have been effective at below-blurring velocities, although most investigators fail to specify the velocities they employed.

Static and Dynamic Perception of Surface Slant. This section presents the results of earlier research by others on the perception of slant or divergence, the main variable of interest in this report. Gibson (1950a) initiated research in this area by determining that a texture density gradient could be a sufficient stimulus for the perception of surface slant. Flock and Moscatelli (1964) and Phillips (1970) showed that, in the utilization of texture gradients, size and shape regularity were more important than regularity in distribution of elements. In comparing the importance of texture gradients and contour convergence Clark, Smith and Rabe (1956a) demonstrated the much greater effectiveness of contour convergence or divergence in eliciting judgments of slant, a result in line with the author's earlier demonstration of human sensitivity to slope information. Youngs (1976) obtained a similar result when he compared linear perspective and binoccular disparity cues for effectiveness in judging slant and found linear perspective more effective. Form ratio, involving the relative shrinkage of certain contours in the figure with

rotation, was also only secondarily useful when compared to convergence (Braunstein & Payne, 1969) in the case of static displays. However, form ratio became a primary factor for dynamic perception; that is, in cases where observers actually watched the rotation of a slanted display (Braunstein & Payne, unpublished study, cited in Braunstein, 1976).

It is interesting that judgments of slant involving either rotation or translation tended to be fairly close to displayed slant while static judgments in contrast were usually underestimates, sometimes by as much as 50%, perhaps, as Braunstein (1976) suggests, because of the presence of conflicting flatness cues in static displays.

3. The Information in Patterns of Blur Lines

Perceptually, the importance of motion blurring stems from the formation of blur patterns in which the individual moving elements appear as fields of semi-parallel blur lines. Figure 3 shows some sketches representing the typical blur patterns that are readily visible directly below a moving observer during the basic types of motion change. In this case the observer is best envisioned as a low-flying pilot. Here the visual system is dealing with fields of semi-parallel curved or straight lines, not with moving points as was previously noted. The apparent lengths of these fleeting blur lines is determined primarily by angular velocity, but also by the amount of reflected light, the wavelength, the state of dark adaptation and the contrast (Harrington, unpublished observations). The relations between type of motion and blur pattern change as illustrated in the figure are as follows:

1. Rate of descent (ascent) is indicated by degree of blur line vergence (convergence or divergence) and where an observer looks in his field of motion will also change the blur pattern vergence he sees.

2. Roll rate is indicated by relative blur line curvature (and relative slope for steady roll rate).

3. Amount of slip is indicated by relative blur line slope.

4. Change in yaw angle is indicated by blur line curvature.

5. Rate of change of the above is indicated by additional blur line curvature superimposed on the appropriate basic pattern.

Work at the University of Oregon by the author (1967), Olson and Attneave (1970) and by Beck (1966a, 1966b, 1967) using line elements has shown that <u>the human visual system is very sensitive to precisely this kind of information</u>, namely relative slope and curvature in fields of lines. Employing a search task where a slope-anomalous element was to be picked out from a field of parallel line segments, Harrington (1967) found that with small slope disparities an observer could respond several orders of magnitude faster than to attributes like disparities in length.

4. Determining Divergence Thresholds

The experiment reported here determined thresholds for detection of motion-produced divergence in terms of the smallest divergence angle that observers were able to see as differing from zero. Thresholds were determined for different parts of the visual field by using nine fixation points ranging from central (foveal viewing) to extremely peripheral (80° visual angle to the side of the fovea). Displays moved at three velocities: slow (20°/sec), medium (40°/sec) and fast (80°/sec). In addition to measuring thresholds the experiment also assessed the extent to which human observers could use divergence information for orientation. Two different methods of simulation were used to create the blur patterns: an optical method which produced "natural" patterns where other variables existed along with divergence and an electronic method which produced "pure" divergence patterns. Finally, displays composed of only 16 elements per frame were compared with displays utilizing a finer texture with 32 elements per frame.

B. DESCRIPTION OF THE EXPERIMENT

Observers were run individually with each observer seated in a darkened booth centered in front of a 5-inch-diameter, circularly-masked Conrac display monitor. Earphones were worn to mask any noise outside the booth; a patch was worn over the left eye as only the right eye was used throughout. During the first session each observer was familiarized with the display parameters, the three velocities of motion of the blur patterns and the nine fixation points he was to employ. The fixation points were lighted letters on the black wall in which the monitor was embedded. The observer's eyes were monitored from outside the booth to be sure he maintained fixation despite the movement on the screen. Only one observer had to be eliminated for inability to maintain fixation.

During actual experimental trials the observer fixated monoccularly prior to each stimulus presentation and afterwards reported whether he had detected any convergence or divergence, gave a measure of confidence in his judgment, and indicated what the perceived effect was in surface orientation (the perceived plane of the blur lines) by orienting a paddle connected to a protractor readout device. The sound track on the video tape was used to instruct and cue the observer. Each trial was two seconds in duration and the interstimulus interval was six seconds. A single session lasted one hour.

Observers were students at the University of Nevada with normal visual acuity, and were paid for their participation. Ten students were run for 15-hours each; one eventually had to be eliminated from consideration because of fixation problems, as noted above.

1. Simulation of Natural Divergence

A video system (Sony camera AVC 3260 and recorder AVC 8640) was selected initially for the simulation and presentation of the rapidly moving blur patterns. It was chosen because its relatively high repetition rate allowed close spacing of the successive dots making up the pattern and because other aspects of stimulus construction were facilitated by this method. To make the situation realistic and to ensure the stimulation of each retinal locus along the trajectory, elongated, nearly overlapping elements were used to form the blur lines. The elements comprising the blur lines moved across the screen at either 20, 40 or 80°/sec, three velocities chosen to represent the range found in naturally occurring blur patterns. The display subtended 10 degrees of visual angle.

a. Stimulus Generation. Five-inch wide rolls of pre-exposed film were used as a black background for the blur pattern elements. Individual elements were made by moving small, rectangular segments of emulsion using a specially constructed guide consisting of a rectangular plastic frame attached to a parallel ruler.

The plastic frame could be adjusted to make elements 1/8" to 1/2" in length, depending on the angular velocity to be used to insure proper spacing from one visual scan to the next. The parallel ruler was used to guide placement and ensure that all elements were parallel. Blur pattern

elements were placed on the background in a random-appearing pattern, with the restriction that either 32 or 16 elements appear in a 4" length of film, to allow determination of the effect of number of elements.

The size of element used for 20°/sec angular velocity trials was 1/8" x 1/8". This value was selected because elements this size were aligned exactly heel-to-toe in successive scans of the video raster; that is, there were no gaps between elements as they moved down the screen, nor was there any overlap. Two film belts were constructed to be used at the 20°/sec velocity. One belt contained 32 elements on every four-inch segment (equal to 32 elements appearing in a single 5" frame). The other belt contained 16 elements per frame.

The size of element for the 40°/sec velocity was 1/8" x 1/4"; for 80°/sec the size was 1/8" x 1/2". Only one belt containing 32 elements/frame was constructed for each of these two speeds.

Once the individual belts were constructed, the film was spliced to form a continuous belt for each velocity which was then placed on a Model MS970 photo interpretation station. The motors of the PIS were calibrated and adjusted to move at the appropriate velocities. The belts were moved over a light table of the PIS, allowing the light to shine through the emulsion-free segments of the film, thus creating a moving light on black display.

A Sony video camera was mounted on a swivel arm which could be placed above the light table of the PIS and moved through a viewing angle of 0°-180°. Figure 4 is a block diagram showing the video equipment.

The camera was adjusted to magnify the elements to cover a 5" area on the Conrac screen. The swivel arm holding the camera was set at a discrete angle and a 2 sec trial recorded on video tape for each angle used.

b. Psychophysical Method. Divergence thresholds were measured using the method of constant stimuli. Pilot data were used to determine a range of five values for convergence and five values for divergence, ranging from almost-never-reported to almost-always-reported. One point was also included at which neither divergence nor convergence existed (the element paths were parallel).

To determine separate thresholds for the nine fixation points, fixation points were assigned randomly to divergence values with the restriction that each divergence appear on the average once with each fixation point. Two random orders of divergence values were video-taped for each speed. These two orders were assembled on a final video-tape in a counter-balanced order so that each divergence value appeared nine times. Separate tapes were made for each of the three speeds. The 20°/sec tape contained photo-interpretation-generated patterns with 32 elements/frame and 16 elements/frame; and electronically generated patterns with 16 elements/frame. The order in which the three types of patterns appeared was counterbalanced. Each observer was exposed to a particular divergence value-velocity combination a total of 90 times throughout the sessions.

2. Simulation of Pure Divergence

After viewing the video-simulated blur patterns in which element size, shape and angular velocity all changed along with divergence, just as they do in the naturally-occurring situation, it was felt that it would be desirable to compare thresholds obtained with these stimuli with thresholds obtained using more tightly controlled or "pure" divergence stimuli, that is, stimuli in which divergence is the only variable that changes in order to assess the role of divergence *per se*. To achieve this purpose a special hybrid-computer blur-pattern generator was designed and constructed, and additional video tapes were made.

A schematic diagram of the synthetic blur pattern generation is shown in Figure 5. Basically, 16 vertical lines are swept, each is divided into 32 steps, only one of which is bright enough to see. This pattern is advanced at a variable rate. Electronically, the frequency of a central clock running at 32kc is successively divided five times in the 32-step per line generator and four more times in the 16-line generator. These nine outputs address a memory containing one bit corresponding to an arbitrary predetermined locus on a vertical line for each line that is generated. The oscilloscope is swept vertically synchronously with the divide chain at $\frac{60}{32}$ hz and the output of the memory is amplified and used to modulate the Z-axis or brightness stage of the oscilloscope. Then for each of the 16 vertical lines one of the 32 positions on it will be painted by the Z modulation producing a random-appearing pattern of 16 elements. This pattern can be advanced at multiples of $\frac{1}{60}$ sec to produce a variable velocity of the pattern. Divergence is produced by adding a variable amount of the sweep signal to the horizontal displacement signal.

3. Comparison with Method of Adjustment

As techniques of display generation advanced, the decision was made to compare thresholds obtained using the method of constant stimuli with thresholds obtained using the simpler method of adjustment. Displays from the hybrid-computer blur pattern generator were used. Observers adjusted a wheel until they could see the blur lines start to diverge. Twenty trials were given for each of five fixation points. Ten observers were each run for approximately one hour.

C. RESULTS AND COMMENTS

Figures 6a and 6b are graphs showing separately the mean thresholds obtained for convergence and divergence at the three speeds and nine retinal loci. An analysis of variance was performed using a three-way randomized-block design (convergence/divergence x speed x retinal loci); Table 1 shows the results. There were no significant effects of direction of vergence (that is, of convergence vs. divergence) nor of speed. The effect of reintal locus on threshold judgment was highly significant as were the variations between observers. Figure 7 shows the resultant thresholds when the data is summed over speeds and shows how the threshold rises with increasing distance from the center of the fovea. Figure 8 shows how much variation existed between one of the most adept and one of the poorest processors of the divergence information found in blur patterns.

Table 2 shows the results of a two-way randomized-block factorial analysis of variance (actual slant x retinal locus) performed on the paddle setting data; that is, on how much error appeared on each trial in the observer's orientation of the surface readout device. Again, retinal locus of stimulation was highly significant as were differences between observers; in addition the actual slant of the displayed surface made a difference in how accurate the observer's judgments were. Additional comparisons were made using Tukey's HSD test. These indicated that errors were smallest when the orientation of the displayed surface was actually vertical; that is, when the elements comprising the blur lines were all parallel and neither convergence nor divergence was present. Consistent underestimation of surface slant appeared to be causing this. Moreover, errors were significantly greater when the displayed surface was tilted with the top toward the subject (converging) than when it was tilted with the top away (diverging). (This may occur because of our greater experience with orienting in natural situations in which terrain rises in the distance.) In addition, significantly greater errors were made when the display stimulated areas further toward the periphery of the eye. This result is in keeping with the higher threshold values found for the same peripheral areas. Similarly, lesser errors were made in the cases of central viewing and viewing only 20° above and below the central point. In terms of orientation accuracy, there were no significant differences between stimulation of the left half of the visual field and stimulation of the right half or between stimulation of the top half as opposed to the lower half. There were no significant differences between the central point, 20° above, 20° below and 40° above despite the fact that there were no significant differences between 40° left, 40° right, 40° below and 40° above.

Figure 9 shows the mean paddle settings observers selected for each of the displayed slants, as well as the perfect-performance line settings would have fallen on if their orientations had conformed perfectly to displayed slant. Note their greater accuracy when the elements are parallel, as noted above, as well as their tendency toward underestimating both convergence and divergence. Figure 10 reveals how much difference there was in orientation accuracy between the most adept and the poorest processors of the information. Observers were rank ordered on the

Table 1
Analysis of Variance Summary Showing the Effects of Convergence vs. Divergence and Fixation Point on Vergence Thresholds

Source	df	ms	F	p
Convergence/divergence	1	39.7		
Velocity	2	184.9		
Fixation point	8	3842.3	19.75	.001
Subject	7	2531.7	13.01	.001
Error	411	194.57		

Table 2
Analysis of Variance Summary Showing the Effects of Actual Display Slant and Fixation Point on Errors in Observers' Settings of Slant

Source	df	ms	F	p
Actual Display Slant	10	11344.2	125.77	<.001
Fixation Point	8	1594.7	17.68	<.001
Subject	7	2204.0	24.4	<.001
Interaction	80	84.4	<1.0	(NS)
Error	686	90.2	---	---

threshold detection and paddle setting tasks and a Spearman rank-order correlation coefficient obtained of .738 ($p < .05$) suggesting that observers who were good at one task frequently tended to be good at the other as well.

Since the authors have seen an indication in the pilot study and other experimental settings of the effectiveness of training in this area, the results here were analyzed for possible practice effects. Errors in vergence judgments were tallied for each of the ten sessions. The mean number of errors for the first three sessions for each speed was computed for five of the subjects (the others had to be excluded because of participation in a short pilot study). The mean number of errors for the last three sessions was also computed. A two-way randomized-block-factorial analysis of variance (speed x first versus last sessions) was performed and the results are shown in Table 3. The reduction in errors with practice was highly significant. The error rate did not vary significantly across speeds, nor was there any interaction between speed and amount of practice.

The effect of method of production was also analyzed. Stimuli differed in representing natural divergence or "pure" divergence and in being composed of either 16 or 32 elements. A two-way randomized-block-factorial analysis of variance (retinal location x method of production) was performed, and the results are presented in Table 4. Neither number of elements employed nor method of production, "optical" vs. electronic, had a significant effect on threshold values. Again, retinal locus of stimulation and differences between observers were significant.

Table 5 shows mean confidence ratings that were given for vergence judgments at different fixation points. Subjects tended to be more confident of judgments near central fixation, indicating a parallel between confidence ratings and threshold values. Confidence ratings used a scale ranging from 1 to 5 where 5 represented a very high level of confidence.

Table 3
Analysis of Variance Summary Showing the Effects of Display Velocity and First Three vs. Last Three Experimental Sessions on Errors in Vergence Judgments

SOURCE	df	ms	F	p
Speed	2	20.2	< 1.0(N.S.)	
First/last	1	2271.4	88.38	<.001
Subject	4	332.3	16.60	<.001
Interaction	2	20.8	< 1	
Error	20	25.7	---	---

Table 4
Analysis of Variance Summary Showing the Effects
of Method of Production and Fixation Point
on Vergence Thresholds

SOURCE	df	ms	F	p
Method of Production	2	354.7	2.08	N.S.
Fixation Point	8	1639.9	9.6	<.001
Subjects	7	891.9	5.2	<.001
Interaction	16	213.9	1.3	N.S.
Error	182	170.9	---	---

Table 5
Mean Confidence Ratings at Different Fixation Points

Mean Confidence Rating	Fixation Point			
	Central	20°	40°	75°
	3.93	3.12	3.04	2.23

Table 6
Threshold Values at Different Fixation Points for the Method of Constant Stimuli and the Method of Adjustment

Method	Fixation Point		
	Central	20°	40°
Constant stimuli	3.2	5.1	7.1
Adjustment	5.2	7.6	8.1

D. DISCUSSION

1. Observers

The variability between subjects was considerable. Certain subjects performed very accurately on both the threshold and the paddle-setting tasks whereas others seemed relatively at a loss on both tasks and additionally during the experiments and debriefing said they could either see no depth effect, no divergence nor both except at extreme settings. The impression was strong that there were two types of observers, one type being weak or even lacking altogether in this type of visual processing. At least one observer in this category did have a history of visual orientation difficulty. Recent neurophysiological findings (Cynader and Chernenko, 1976) and previous perceptual observations (Pantel and Picciano, 1976) have shown the possibility of separate visual system processors for form, for motion and for location and presumably the optimal pilot should possess a facility with each. It may be that a test involving blur pattern perception or at least motion field perception would be useful for pilot screening. Further study of this individual difference seems desirable.

2. Position in the Visual Field: Central vs. Peripheral Viewing

The results of varying fixation points indicate that by far the most efficient use of blur pattern divergence is possible with central viewing. Thus in a viewing situation where other factors do not dictate otherwise, the observer should look generally to the front or slightly left or right of center where blur pattern divergence and blur pattern divergence change from one local area to the next are both most richly represented. Similarly, the imaging device of a remote piloted display should be pointed forward and the viewing screen and windows should be located so that when blur pattern information exists, it can be viewed foveally. Under special conditions such as the white-outs experienced, for instance, in Antartic landings, it may be more feasible to view artificial textures on the ice placed closer to the aircraft. Alternately, if the piloting task requires the fovea for other tasks such as instrument reading, then the blur pattern can be presented all around the fovea with the peripheral retina serving perhaps less well, but still effectively.

In general, the closer to the fovea the better. Fixation points that were closest to central viewing showed threshold values of 5.1° and were superior to the next closest to center with threshold values of 7.1°. The two farthest points respectively were worse for performance than all the others; however, there were differences in placement with the nasal retina, corresponding to fixating the extreme right field with the right eye in these experiments, being the worst in performance and also by subject report. This result was not expected since other retinal asymmetries favor the nasal retina (Chapanis, 1949).

3. Display Velocity

Performance at the different angular velocities of 20, 40, and 80° /sec was equally good. One major implication for piloted display design and perhaps for simulators as well is that directional information can be

imparted with blur patterns without attention to actual craft velocity. It may even be that static lines could be effectively used on the screen as abstractions of blur pattern information, at least foveally, in conjunction with ordinary video methods which often fail to give information that visual line analyzers could use. Of course the lack of a velocity effect in these experiments doesn't imply that velocity gradients are unimportant generally.

4. Convergence-Divergence

Observers performed equally well in terms of threshold values whether the blur patterns diverged at the bottom as they would in ordinary flight or converged at the bottom as they would if the observer were flying inverted even though none of the subjects had appreciable experience with the latter variety of blur pattern contrary to the situation with bottom divergence that is seen all the time. There was some difference, however, in terms of ability to orient (see Results section).

5. Number of Elements

The comparison using optically-generated blur patterns of 16 vs. 32 elements was not significant. This is fortunate from a simulation and motion display point of view. It may be that for the simpler aspects of blur pattern divergence processing even fewer elements are needed. Still further experimentation is suggested to see if very fine textures with a great many elements might not carry blur pattern information more effectively. Perhaps in this context the difference between 16 and 32 elements is small, although in some other conditions involving line elements with common slope, information is greatly enhanced by an increase of this magnitude in number of elements (Harrington).

This finding also is very important with regard to runway texturing for it indicates that adequate results can be obtained without especially high-density texturing when conditions of poor visibility or unusual circumstances require more than just the normal surface texture, runway lights, etc.

6. Natural vs. Synthetic Patterns

There was no significant difference in performance between viewing of "natural" as opposed to synthetic blur patterns.

This is surprising and again important for synthetic displays because the natural patterns contain so much more motion-related information of a sort that has been shown to be visually useful in similar circumstances. Naturally-occurring blur patterns have gradients of element velocity, element size and element density, as well as divergence. The synthetic patterns electronically produced for these experiments have elements of unchanging size and density that move with unchanging velocity and differ from one trial to the next only in the amount of divergence between element trajectories. Element velocity (von Hofsten, 1973), size change (Ittleson, 1951) and element density (Gibson, 1950b) have each been independently shown to be quite powerful determiners of depth perception. It is interesting that the blur pattern displays were not appreciably enhanced by them when divergence itself was so important.

Electronically, a pure-divergence pattern is not as difficult to simulate as one bearing additional variables and it is fortunately suggested by these results that a synthetic display can get by without them. This is also significant from a neural modeling point of view because theoretically only slope-sensitive line-analyzing units, not motion- or size-detectors, are needed to account for our observers' performance.

7. Orientation Paddle Settings

Most of the observers were consistent at setting the paddle but all underestimated the tilt of the simulated element plane. This coincides with the finding previously cited that subjects viewing line patterns exhibiting divergence consistently underestimate what the surface tilt would be if these were actually parallel lines in 3-dimensions.

An important implication of this is that any actual simulations *might require compensations in divergence* such that the observer need be presented with divergences that are exaggerated in order to bring about an accurate perception.

8. Practice Effect

The results indicate that sensitivity to the divergence information in blur patterns can be increased through practice. This taken along with other evidence would seem to suggest the desirability of training programs in this area.

E. THE RELATION OF THE DISPLAYED BLUR PATTERNS TO ACTUAL FLIGHT

Divergence of a blur pattern on the diaply is defined here as the angle between the right and left outermost lines possible for a given display (see Figure 2). This fixed-viewing angle definition is appropriate to the remote piloted display situation and to the case where one has a restricted view as in looking through a porthole. Each possible blur pattern on the display with a given divergence corresponds to blur patterns that are seen by a moving observer along two loci on the ground, one fore, one aft, referred to here as isoverges. This situation is illustrated in Figure 11 and one isoverge is shown. It should be noted that this discussion is concerned with the geometry of which display blur patterns map onto which blur patterns on the ground, seeming indistinguishable from one another to the pilot, not with how the pilot sees either of them. It will be proven that the nature of the isoverges along a straight line of flight is determined completely by the height of the observer and his angle of climb or descent. In simulating normal straight-line flight the blur patterns either diverge at the bottom of the display, the elements moving top to bottom to the front of the pilot and bottom to top to his rear, or they are parallel as when he looks directly to the side or straight down.

Viewing Figure 11 again, the blur lines on the display ideally can be regarded as projections to the eye of the blur lines on the ground. Actual trajectories of the textural elements on the ground plane are of course parallel. If a plane is passed through the eye and through a particular element's trajectory on the ground, corresponding to some blur line, then this plane's intersection with the display will be the particular display trajectory that would be required to simulate the blur line on the ground. The figure shows this for two special blur lines, those that are tangent to the display. These are not actually seen on the display but represent the limiting case of the blur lines that are seen there and are useful in defining divergence in the experimental context.

The two planes labeled "tangent plane" contain these extreme display blur lines, and also contain the eye and the corresponding blur lines on the ground. Similarly, for any blur lines on the display a plane exists that contains the eye and a corresponding blur line on the ground.

It is important to notice that any such plane will also contain the line of flight because the line of flight is parallel to the lines on the ground and passes through the eye. Two planes each containing one of two parallel lines and intersecting at a point (the eye) necessarily contain a third parallel line passing through that point (the line of flight). Thus any plane of the family just discussed, containing the eye, a blur line on the ground and one on the display will contain the line of flight.

The geometric situation then can be viewed as involving an infinitely-numbered family of planes through the line of flight. Two of these are the tangent planes in the figure. Now if one wishes to know what viewed point on the ground will produce a blur pattern with some given divergence on the display, it is only necessary to consider that for a given divergence angle the distance from the center of the display to point A on the line of flight must remain constant because the tangent planes,

which must contain the line of flight, would be spread apart if this distance were shortened and would come together if the display dropped down, thus changing the divergence. In the experiments the distance from the display to the eye was carefully controlled; therefore, in the model this distance can also be considered to be a constant. Also the line of sight was carefully kept perpendicular to the display so the angle between the line of sight and the line from the display's center can be considered a right angle. Therefore, for any displayed blur pattern with fixed divergence there is a rigid right triangle composed of the line of flight from the eye to point A, the line of sight from the eye to the center of the screen, and the line from there to point A.

The only dimension of freedom in the geometry of this viewing situation, if divergence is held constant, is a rotary one. The rigid right triangle can be swung around the line of flight. Then the line of sight generates a circular cone referred to here as the equal divergence cone. When a cone intersects a plane (e.g., the ground plane) a conic section is generated (circle, ellipse, or hyperbola).

Thus a particular divergence on the display will correspond to the divergences in a blur pattern from the ground plane when the line of sight falls anywhere on the conic section that corresponds to that divergence. It would seem appropriate to name these conic sections isoverges. An hyperbolic isoverge is seen in the figure.

Since the divergence of blur patterns does not depend on velocity in straight and level flight, for each height above the ground a unique patterning of blur pattern divergence can be seen. In order to interpret the threshold data from these experiments it is desirable to know how much divergence would be seen when looking at each point on the ground.

For a fixed divergence and height, h, the equal-divergence cone of regard in a right-handed three-dimensional coordinate system could be characterized mathematically as

$$X^2 + (Z-h)^2 = C^2Y^2 \qquad 1)$$

In relation to Figure 11, the origin is in the ground plane below the eye, the x-axis is to the right, the y-axis is below the line of flight and the cone is generated by the line of sight. C is a constant determining the openness of the cone and will be related to the divergence angle. C can be determined by considering the case where the cone intersects the y-axis. Mathematically this is done by setting X and Z = 0 in the equation. Then

$$h^2 = C^2Y^2 \text{ or } C = \pm \frac{h}{Yo} \qquad 2)$$

Yo is the distance from the origin to the intersection of the cone and the y-axis.

The equation of the hyperbolic isoverge can be obtained from the intersection of the cone and the ground (x, y) plane. This is found by setting Z = 0 in the equation of the cone giving

$$X^2 + h^2 = C^2Y^2 \qquad 3)$$

Substituting for C gives

$$X^2 + h^2 = \left(\frac{h}{Yo}\right)^2 Y^2 \tag{4}$$

In order to relate this hyperbolic isoverge to display divergence it is helpful to realize that the display divergence will be the same anywhere that the line of sight intersects the isoverge, thus the case is simplified by finding the divergence in the Y-Z plane.

$$Yo = h \cot S \text{ or } S = \operatorname{arc\,cot} \frac{Yo}{h}, \tag{5}$$

where S is the angle that the line of sight makes with the y-axis and also the angle of declination of the line of sight. Let the distance along the line of sight from the eye to the display be d and the distance from the center of the display to the point A be Q.

$$S = \operatorname{arc\,tan} \frac{Q}{d}. \tag{6}$$

If a line, r, is drawn from the center of the display to the point where the line AB in the figure is tangent to the display it will be perpendicular to this line. Then 1/2 the divergence angle,

$$\frac{\alpha}{2} = \operatorname{arc\,sin}\left(\frac{r}{Q}\right), \tag{7}$$

$$\text{where } Q = d \tan S = d \tan\left(\operatorname{arc\,cot} \frac{Yo}{h}\right), \tag{8}$$

$$\text{and, from Eq. 3, } Q = \frac{dh}{Yo}.$$

$$\text{Therefore } \frac{\alpha}{2} = \operatorname{arc\,sin}\left(\frac{rYo}{dh}\right). \tag{9}$$

From eqs. 9 and 4,

$$\alpha = 2 \operatorname{arc\,sin}\left(\frac{rhY}{dh\sqrt{x^2 + h^2}}\right).$$

$$\alpha = 2 \operatorname{arc\,sin}\left(\frac{rY}{d\sqrt{x^2 + h^2}}\right).$$

Three-dimensional plots of this function are shown in Figure 12 where the height of a surface above a particular point (x, y) equals the amount of divergence an observer moving at height h and located at o would see in the blur pattern at that point. This is illustrated in the figure for three different altitudes.

Figures 13 and 14 show isoverges to the front of an observer moving straight and level with his eye respectively at 5.5 and at 55 feet above the ground. In each case the approximate region is shaded wherein the

the observer would fail to detect divergence when viewing foveally if his divergence threshold was average.

F. THE ROLE OF DIVERGENCE IN ORIENTATION OF A MOVING OBSERVER

The experiments reported here have conclusively shown that human processing of blur pattern divergence information is adequately sensitive to make that information as its commonly encountered in low-level flight, automobile driving and even walking potentially a powerful orientation aid. There are several ways in which relative blur line slope or divergence can be used alone as an orientation aid.

The divergence threshold results presented here are interpretable in terms of roll, yaw and drift. Assuming a 5° threshold, then even without any reference like the side of the aircraft a five degree yaw or drift is detectable probably decause the blur line coming directly at the observer will not appear to come from the front but rather from 5° to the side. It is probable that our results can be generalized thus. Also reference to the side of the craft would give indications of a 5° yaw or drift and of a roll rate that would depend on forward velocity. It is suspected that if a blur line is extremely close to the side of the craft, especially if the side is parallel to the axis of motion, that the proximity and possibly the disappearance of the blur line behind the edge of the craft previously mentioned would allow detection of drift or yaw of considerably less than 1°. Accordingly line patterns could be put on sections of the windows of an aircraft so that the blur patterns from the ground could be viewed through them for comparison. It may be that a moire effect would be generated causing the pattern to change brightness or flicker in a way that would be visible peripherally. For example the line pattern specific to the proper attitude, altitude and sink rate for flaring the aircraft during landing could be matched with an appropriate texture on the ground.

Blur pattern divergence is also potentially very powerful when used in conjunction with other visual correlates of motion. The overall situation is extremely complex but the following examples will suggest some ways divergence information might be used in conjunction with other variables. Information about a unique location in three-dimensional space can come from the divergence pattern as it changes over time or from other aspects of the visual array such as blur line length (which has been shown to be a concomitant of angular velocity). Other possible sources include such sensory input as that of the inner ear combined with visual eye movement feedback, or the knowledge that the subject may have about the visual array such as the size of a carrier deck or information about its texturing.

The actual utility of blur pattern divergence will depend on the conditions of motion and of viewing. For the purpose of illustration consider the following simplified case representing relations of divergence to orientation.

If an observer is flying straight-and-level above a textured surface and observes a specific blur pattern with only divergence from a porthole in his craft but has no other information about his location in the craft nor of the craft's location, he can ascertain, from the divergence angle in the blur pattern that he is looking down a generator of the surface of

a specific cone whose axis is the line of flight (see the preceding model) but he cannot state which of the cone's generators his line of sight corresponds to nor how far it is to the ground.

Except under the most unusual cases in space flight, the observer in addition can use the orientation of the blur pattern in his porthole, namely whether its lines proceed symmetrically to either side of vertical (as related to his craft, not the ground), whether they go from left to right, top to bottom, etc. He then knows which of the cone's generators he is sighting down, essentially what his roll angle is, but he still does not know his distance from the textural elements on the ground that are creating the pattern.

Finally, this distance and thus the precise momentary location can be ascertained in a number of possible ways. The blur line length, though it will interact with intensities and contrasts in the pattern in a flight situation, is potentially under control in a remote piloted display. Therefore, it can help indicate angular velocity and there will be gradients of angular velocity both up and down and cross-ways on the screen. It is known (Whiteside & Samuel, 1970) that at given aircraft velocities texture elements of equal angular velocity for the observer can be found on the surface of a torus. These can be used alone or in conjunction with known flight parameters gained from the instruments, such as ground speed. Well-advised texturing of the surface and the observer's awareness of that texturing can give absolute distance, even though high velocity may cause blurring, through blur line width and separation and the number of blur lines visible through the porthole. Also, normal bouncing of the observer causes side-to-side oscillations of the blur pattern lines. This information combined with that from the inner ear can give absolute distance information even though velocity has obliterated the usual static information.

The actual dimensions that the observer does use in a particular situation obviously can be expected to vary widely among the very large number of possible permutations of the variables in the example and there are quite a large number of other situation-specific variables that would be useable in conjunction with blur pattern divergence.

A total analysis of the entire situation has never been accomplished even before this introduction of blur pattern parameters; at the present state of perceptual knowledge, it is probably most feasible to analyze each landing, guidance, simulation or remote-display design situation on a case-by-case basis. To that end, the research presented here has quantified where in the visual field of a moving observer useable blur pattern divergence on a 16 or 32 line 5°-display can be found that could be mixed with the manifold of other variables to give orientation information. An investigation now being carried out on curvature in blur patterns should enhance the status of the blur pattern as a potential conveyor of motion information, partly because curvature, unlike divergence, does change with distance and may combine with divergence to give unique position information from a momentary exposure to a blur pattern.

Thus far only absolute threshold for divergence has been considered. Even though this by itself has given valuable information about the orienting

potential of a rapidly-moving observer, the primary reason for studying absolute divergence thresholds has been to provide a basis for studying certain other aspects of blur pattern divergence that are even more powerful potentially. Studies are now underway to investigate differential thresholds for blur pattern divergence. The surface in Figure 12 showed the divergence available to a moving observer at any point on the ground and indicated that there are unique patterns of divergence change at different parts of the field; thus it is possible that the observer may be able to highly refine his judgments about his parameters of motion, depending on his differential threshold for divergence, by using this change of divergence over space.

Ordinarily divergence also changes over time--during altitude change, pitch, etc. and preliminary work shows that blur pattern changes over time may stimulate the visual system with surprising effectiveness. During the coming year the laboratory will be investigating this human perceptual sensitivity also.

Perhaps the most easily perceived blur pattern information occurs when a blur pattern is next to a straight edge that can be used as a reference. If the pattern moves nearly parallel to the edge then blur lines disappear behind it. This is a very sensitive indicator of yaw, drift, and roll and it will be investigated also.

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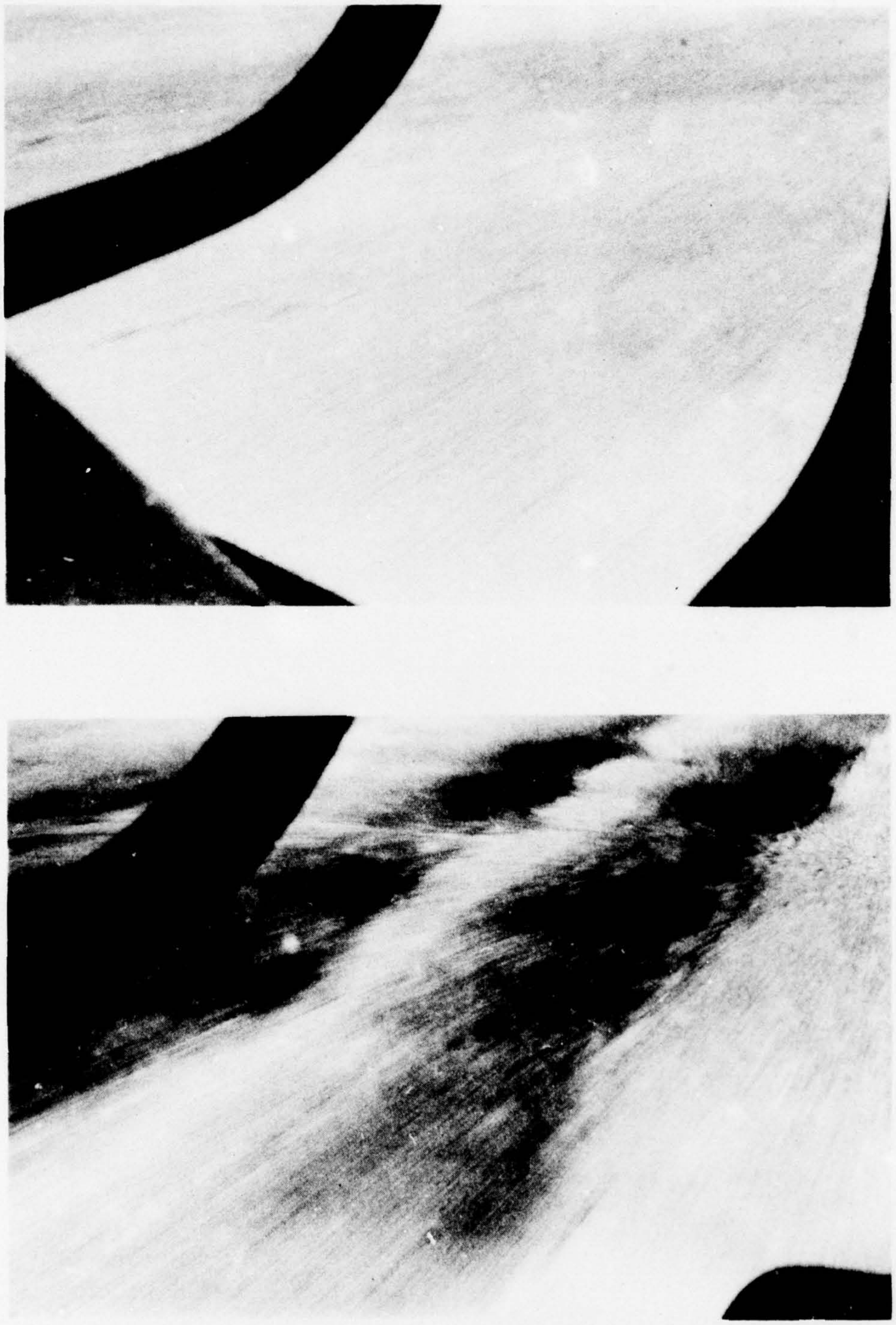


FIGURE 1

Typical Blur Patterns Taken From an Aircraft

The upper photo showing divergence was taken to the front shortly before take-off; the lower, showing divergence and curvature, was taken during landing.

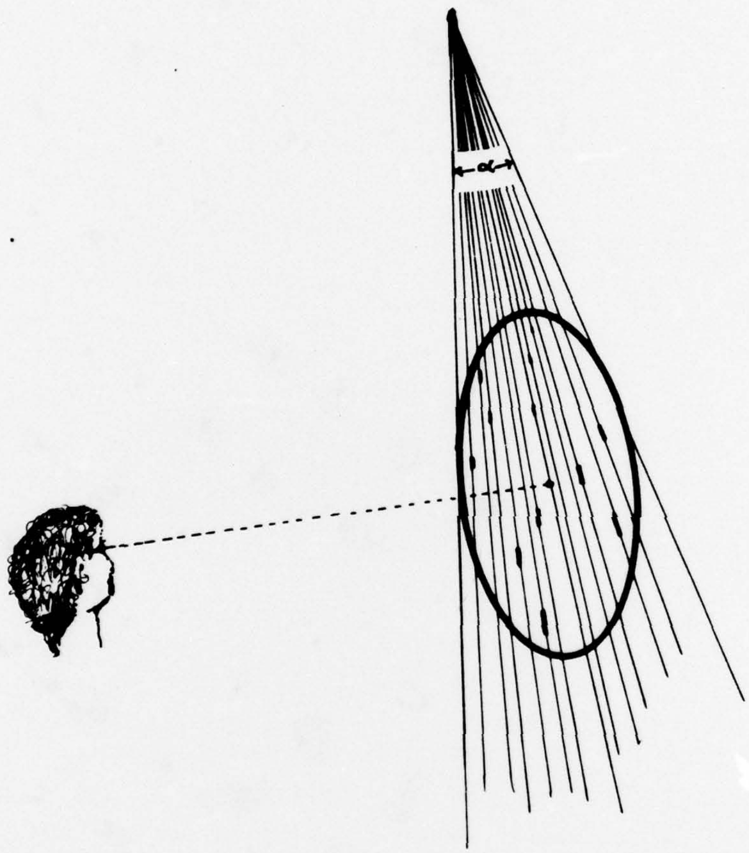


FIGURE 2

A Divergent Display

The divergence angle, alpha, is defined as the angle between the extreme-most possible blur line trajectories at the left and at the right of the display. Divergence so defined depends upon the size of the display. The situation is analagous to a moving observer's view through a porthole in his craft.

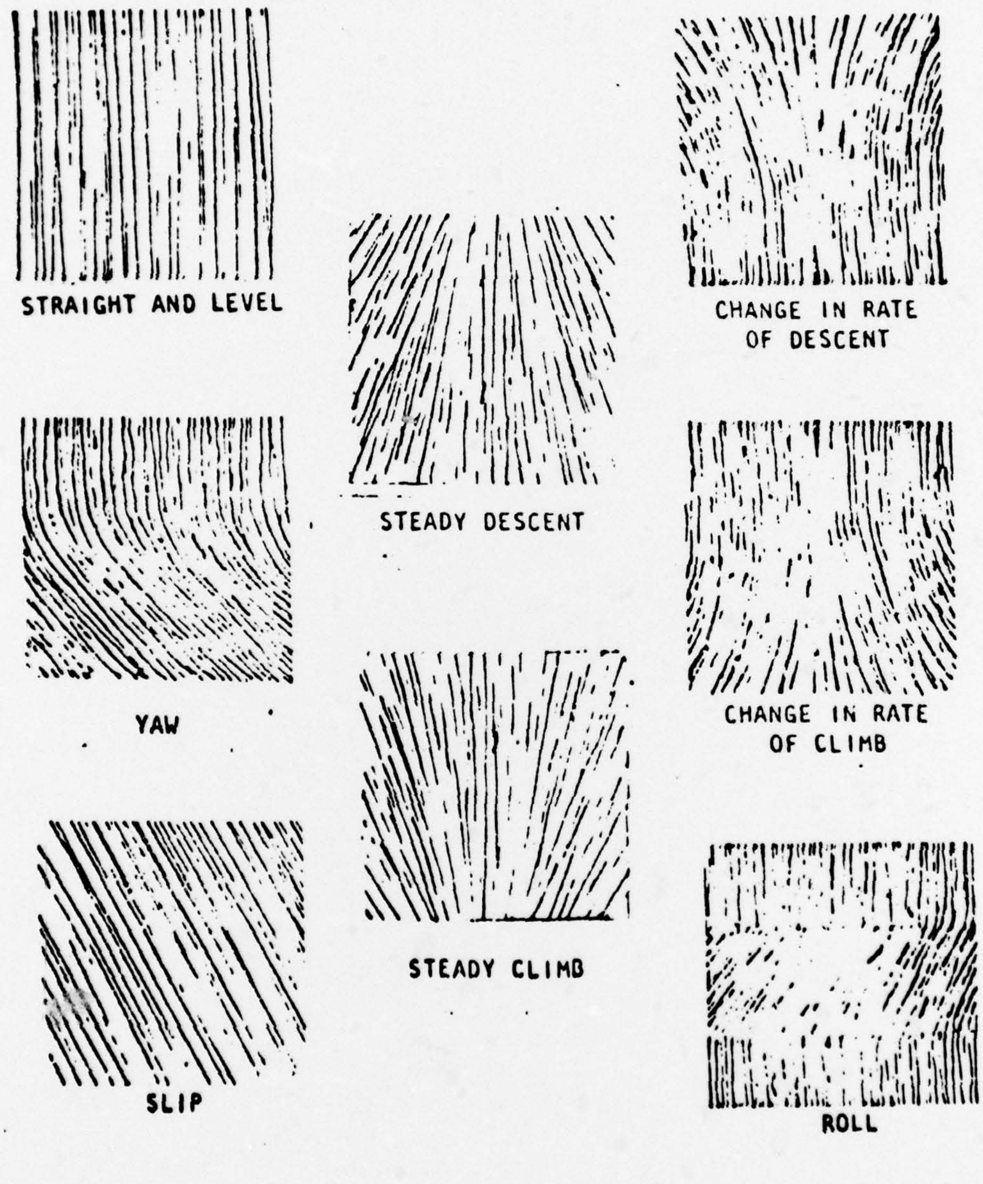


FIGURE 3
Blur Pattern Correlates of Attitudes of Movement

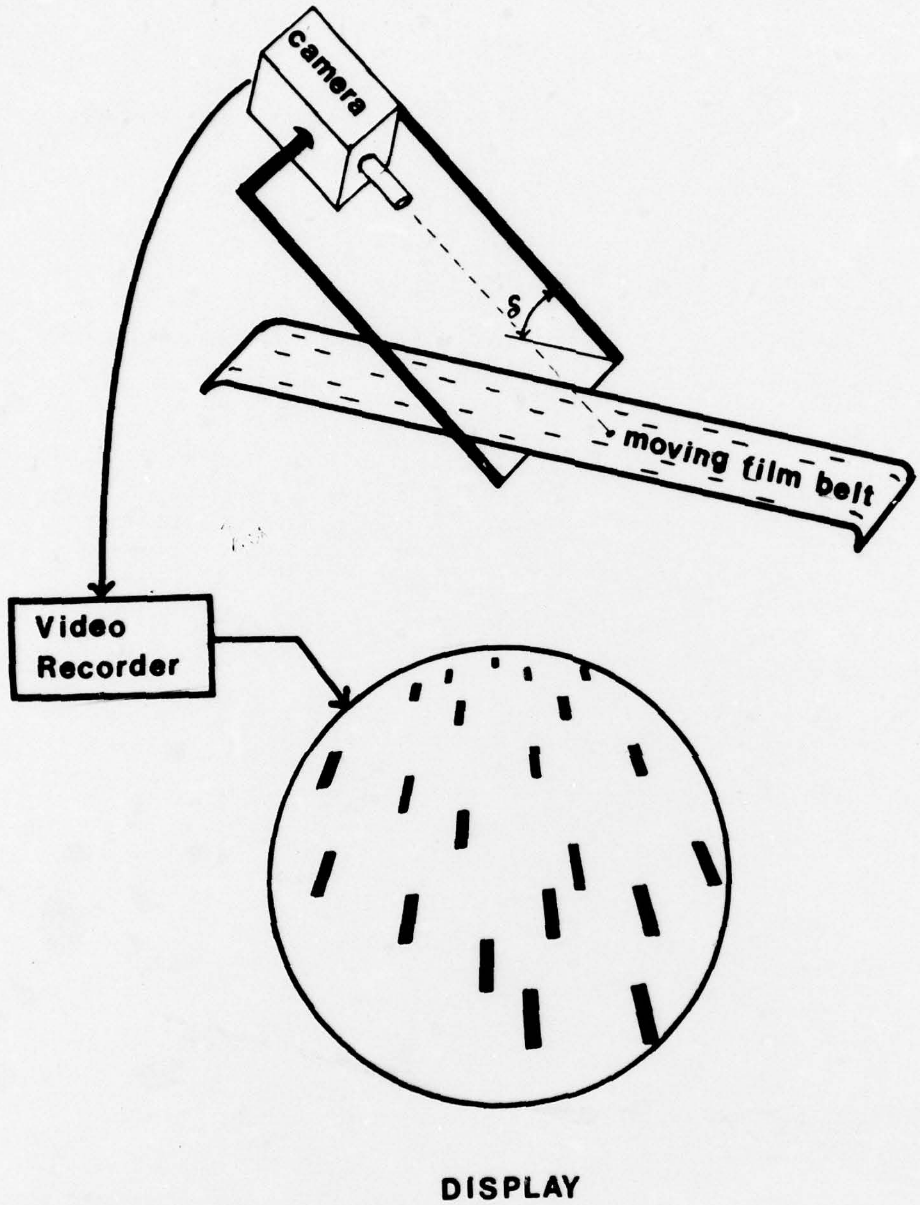


FIGURE 4

Optical Stimulus Generation

A belt of moving photographic film bears line segments that are viewed by a video camera whose angle of regard, delta, is variable in order to produce different degrees of divergence of the element paths on the display monitor.

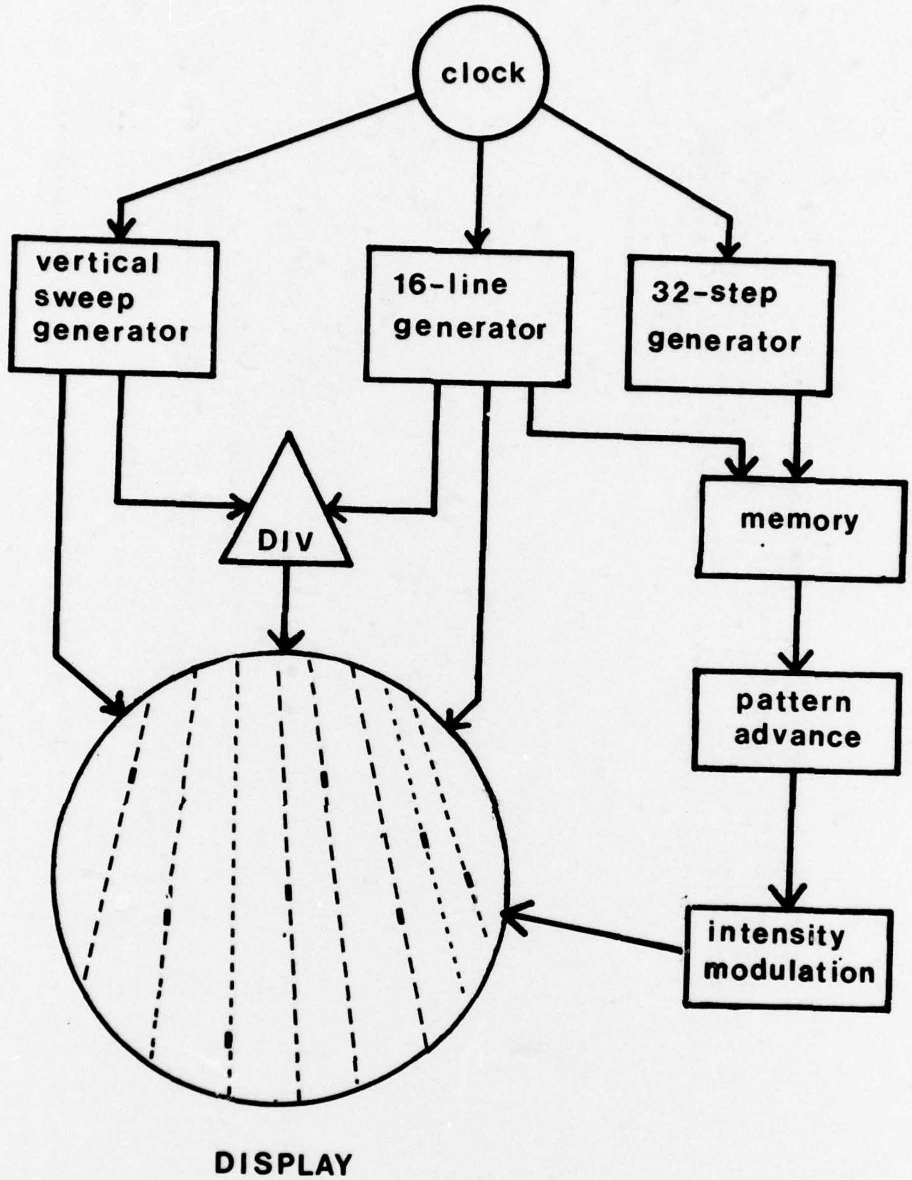


FIGURE 5

Schematic diagram of the synthetic blur pattern generator

In common synchronization with the clock, vertical lines on the display are produced by the vertical sweep generator, displaced successively from left to right by the 16-line generator and modulated to produce one element per line by the 32-step generator, the memory and the intensity modulator. Divergence is produced by mixing varying amount of sweep signal with the horizontal displacement generator.

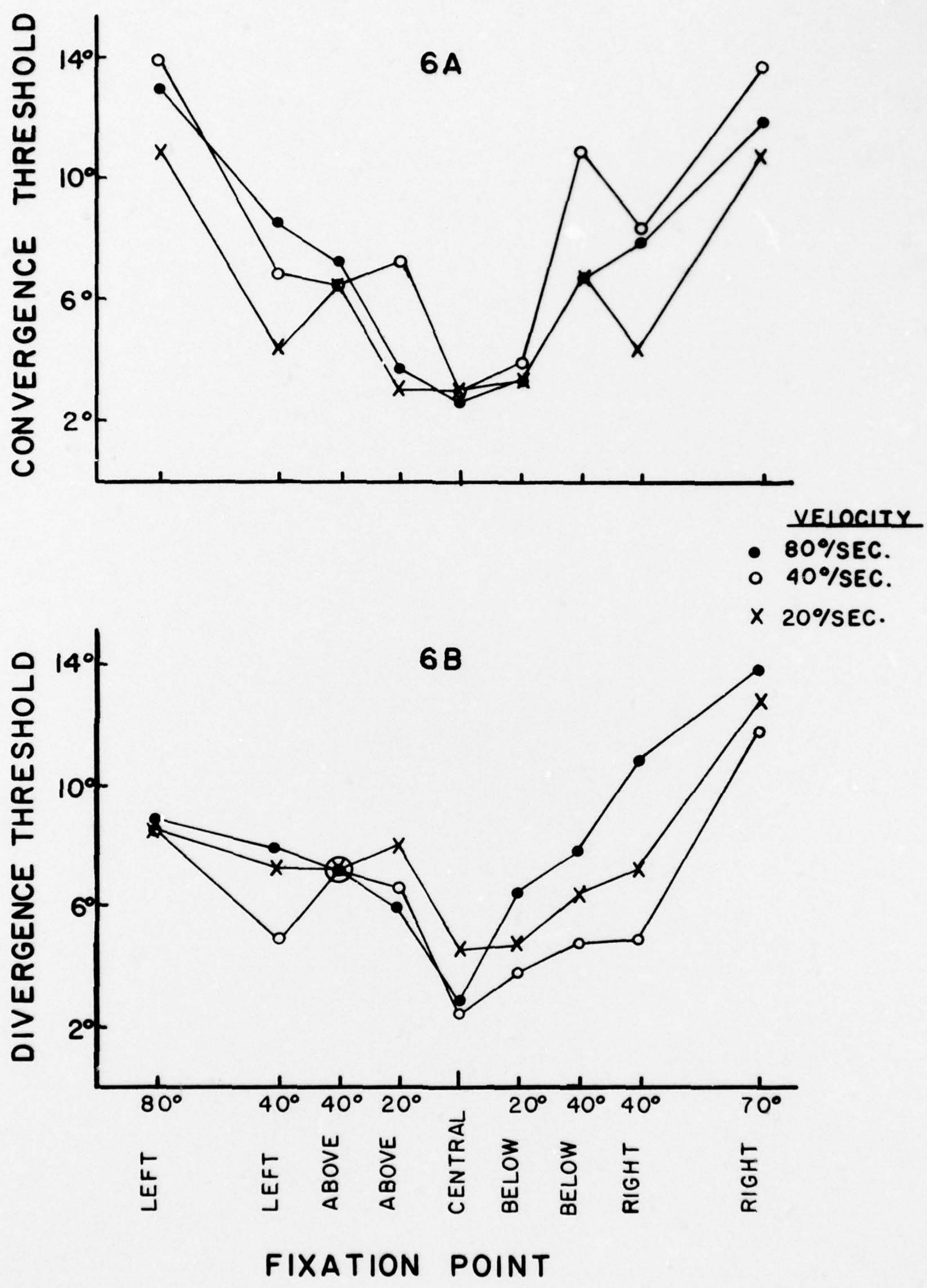

6A
CONVERGENCE THRESHOLD
14°
10°
6°
2°
VELOCITY
80°/SEC.
40°/SEC.
20°/SEC.
6B
DIVERGENCE THRESHOLD
14°
10°
6°
2°
80° LEFT
40° LEFT
40° ABOVE
20° ABOVE
CENTRAL
20° BELOW
40° BELOW
40° RIGHT
70° RIGHT
FIXATION POINT

FIGURE 6

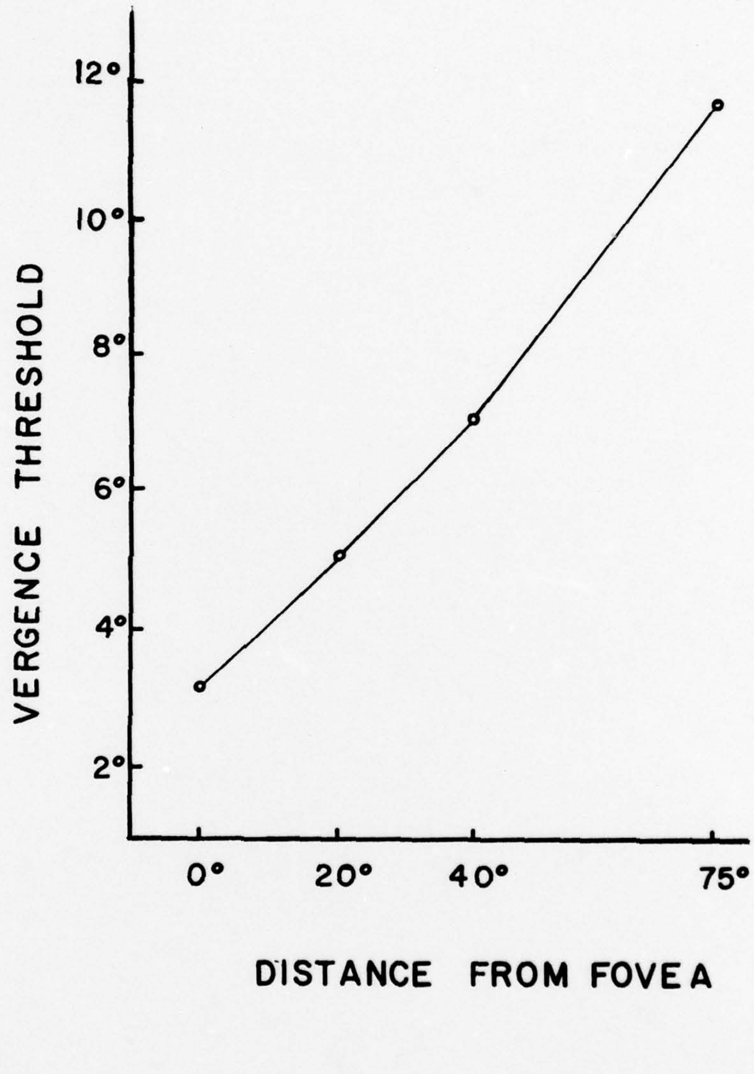
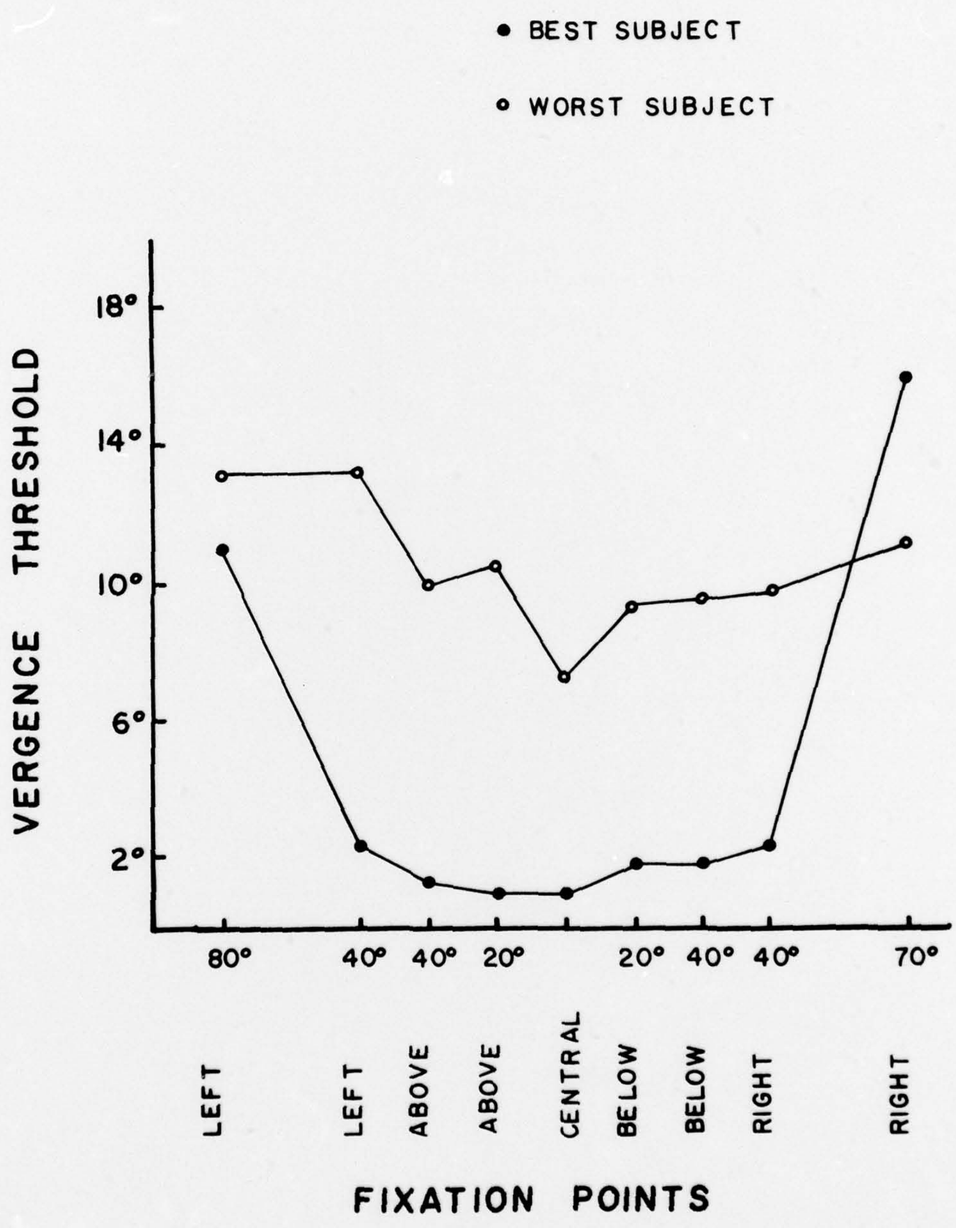


FIGURE 7



● BEST SUBJECT
○ WORST SUBJECT
VERGENCE THRESHOLD
18°
14°
10°
6°
2°
80°
40°
40°
20°
20°
40°
40°
70°
LEFT
LEFT
ABOVE
ABOVE
CENTRAL
BELOW
BELOW
RIGHT
RIGHT
FIXATION POINTS

FIGURE 8

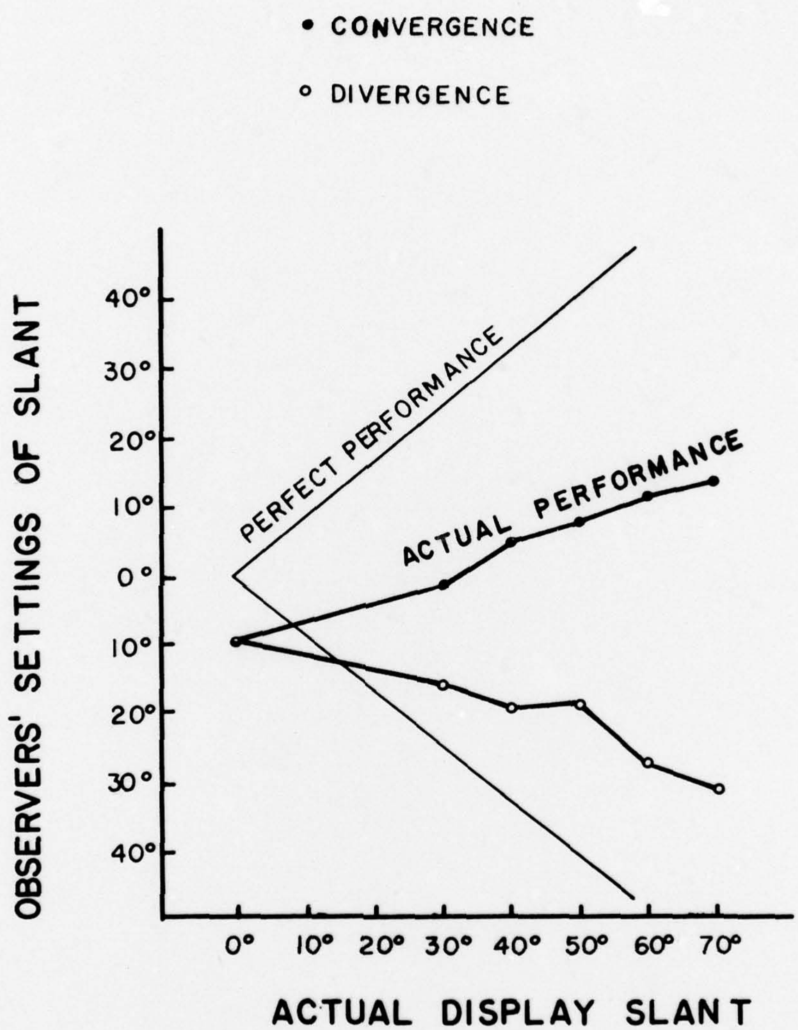

• CONVERGENCE
o DIVERGENCE
OBSERVERS' SETTINGS OF SLANT
40°
30°
20°
10°
0°
10°
20°
30°
40°
PERFECT PERFORMANCE
ACTUAL PERFORMANCE
0°
10°
20°
30°
40°
50°
60°
70°
ACTUAL DISPLAY SLANT

FIGURE 9

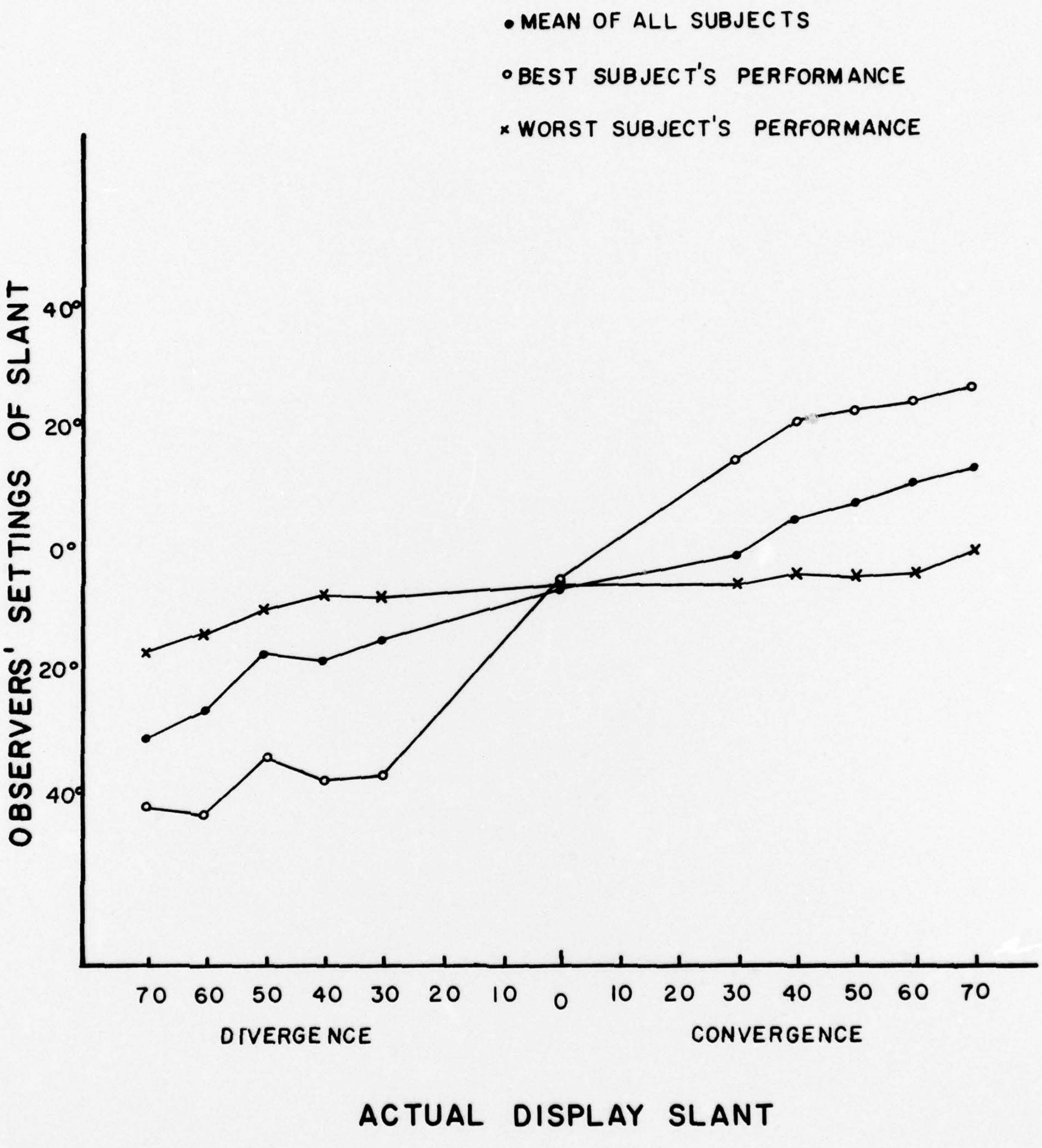

• MEAN OF ALL SUBJECTS
○ BEST SUBJECT'S PERFORMANCE
× WORST SUBJECT'S PERFORMANCE
OBSERVERS' SETTINGS OF SLANT
40°
20°
0°
20°
40°
70 60 50 40 30 20 10 0 10 20 30 40 50 60 70
DIVERGENCE
CONVERGENCE
ACTUAL DISPLAY SLANT

FIGURE 10

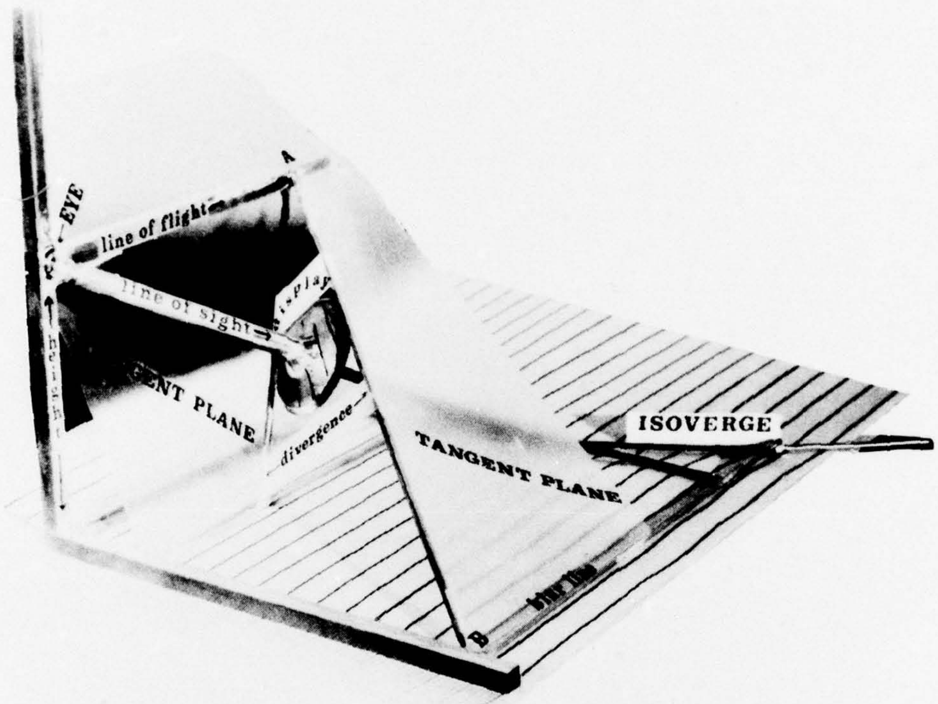


FIGURE 11
Divergence in the Projection of Blur Lines

A blur pattern with any given divergence will be seen by an observer moving over a plane if and only if his direction of gaze intersects the conic section (isoverge) corresponding to that given divergence.

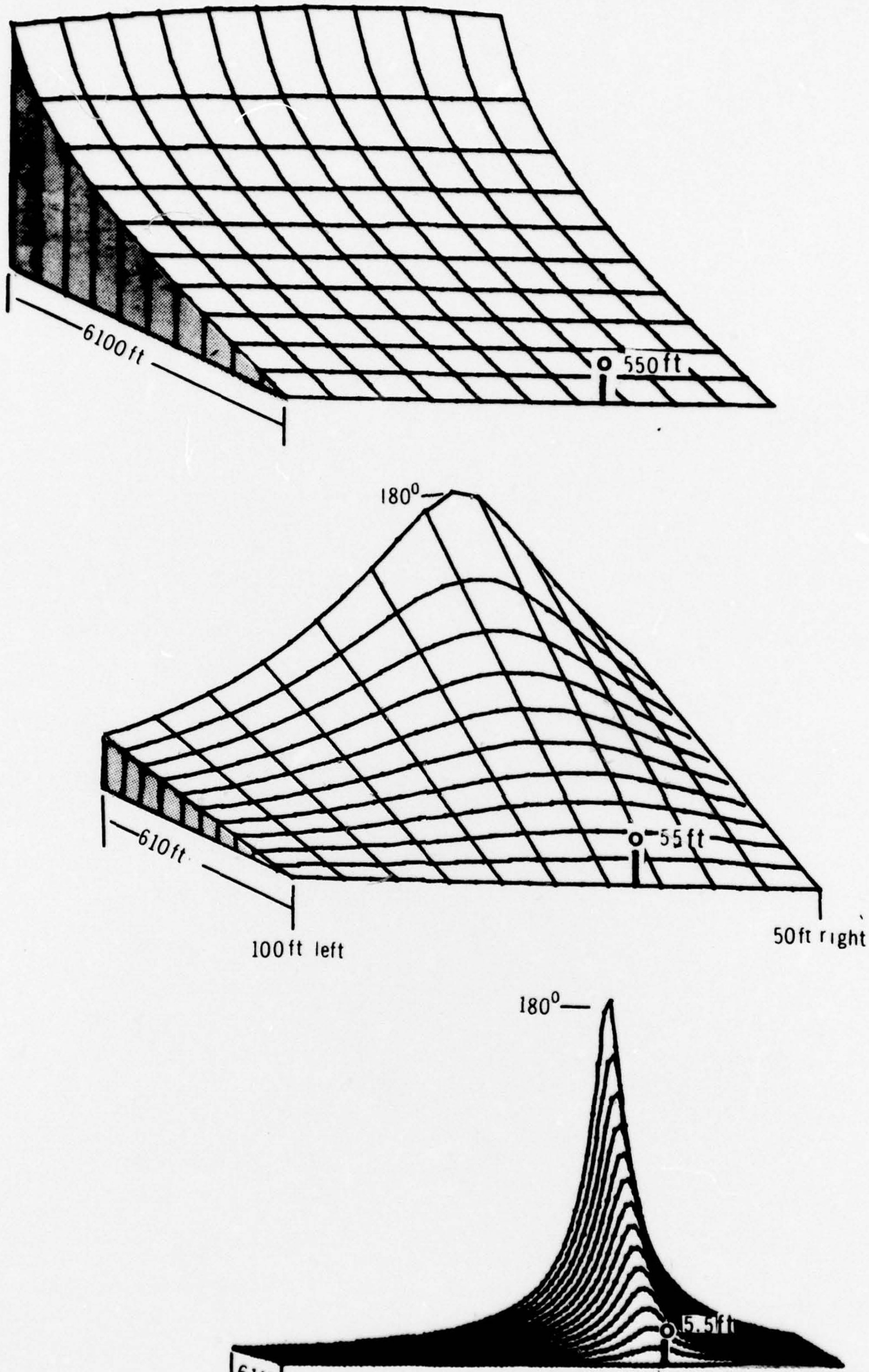


FIGURE 12

The blur pattern divergences seen on the ground by the observer(O) whose eye is located at the altitudes indicated. In each case the surface extends 100 ft. to the left, 50 ft. to the right and to the front until the maximum divergence angle of 180° is reached. The amount of divergence at a given point is given by the height of the surface. Surfaces have been rotated left to facilitate viewing.

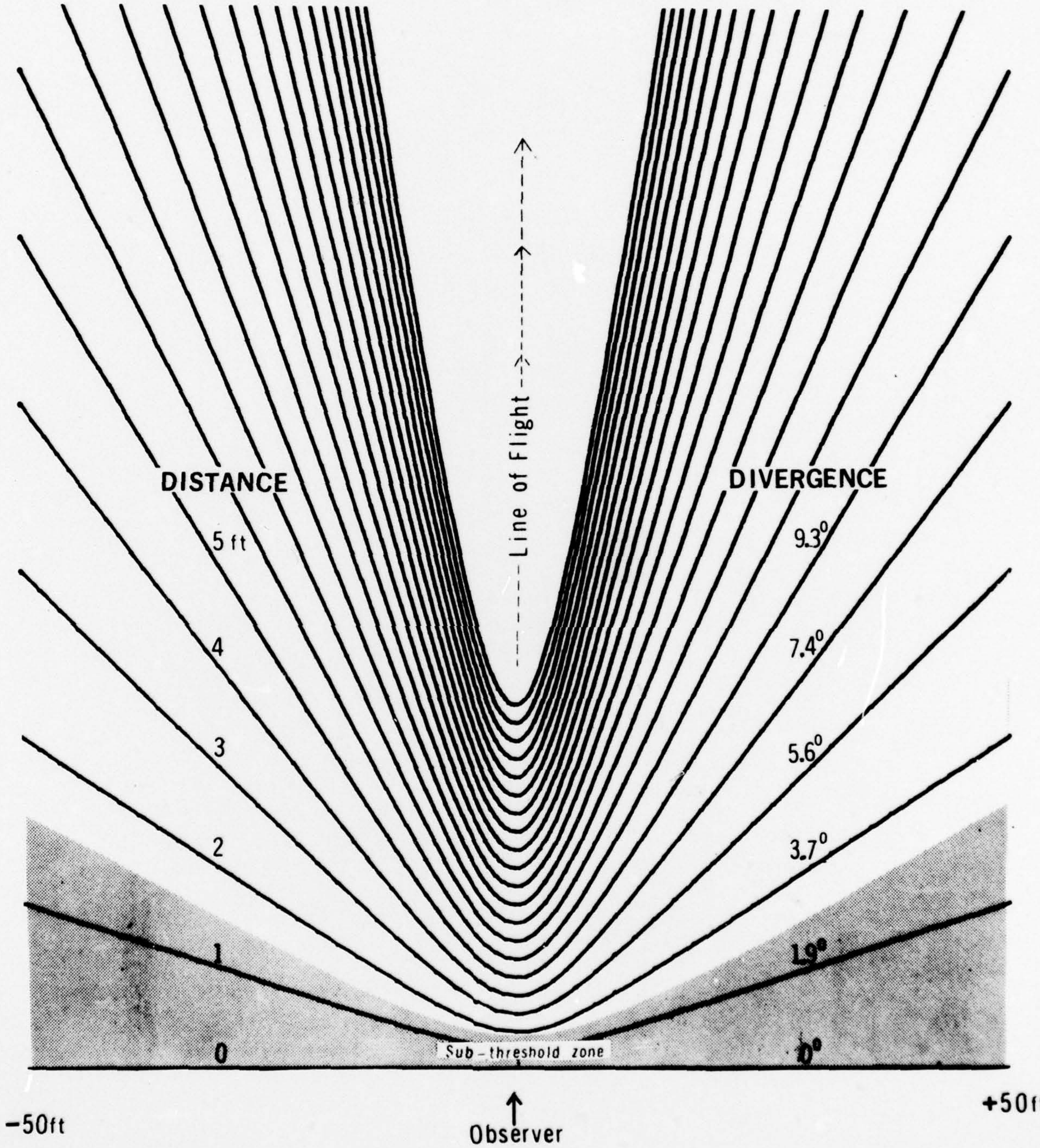


FIGURE 13

Isoverges to the fore of an observer moving straight and level with his eye 5.5 ft. above the horizontal plane in the direction indicated by the arrow. Distances are from the observer to the respective hyperbola. The actual divergence angle that each isoverge represents is shown. For example, anywhere along the contour labeled 3 ft. the observer will see a divergence of 5.6°. All divergences below average foveal threshold as determined by the experiments lie approximately in the shaded zone.

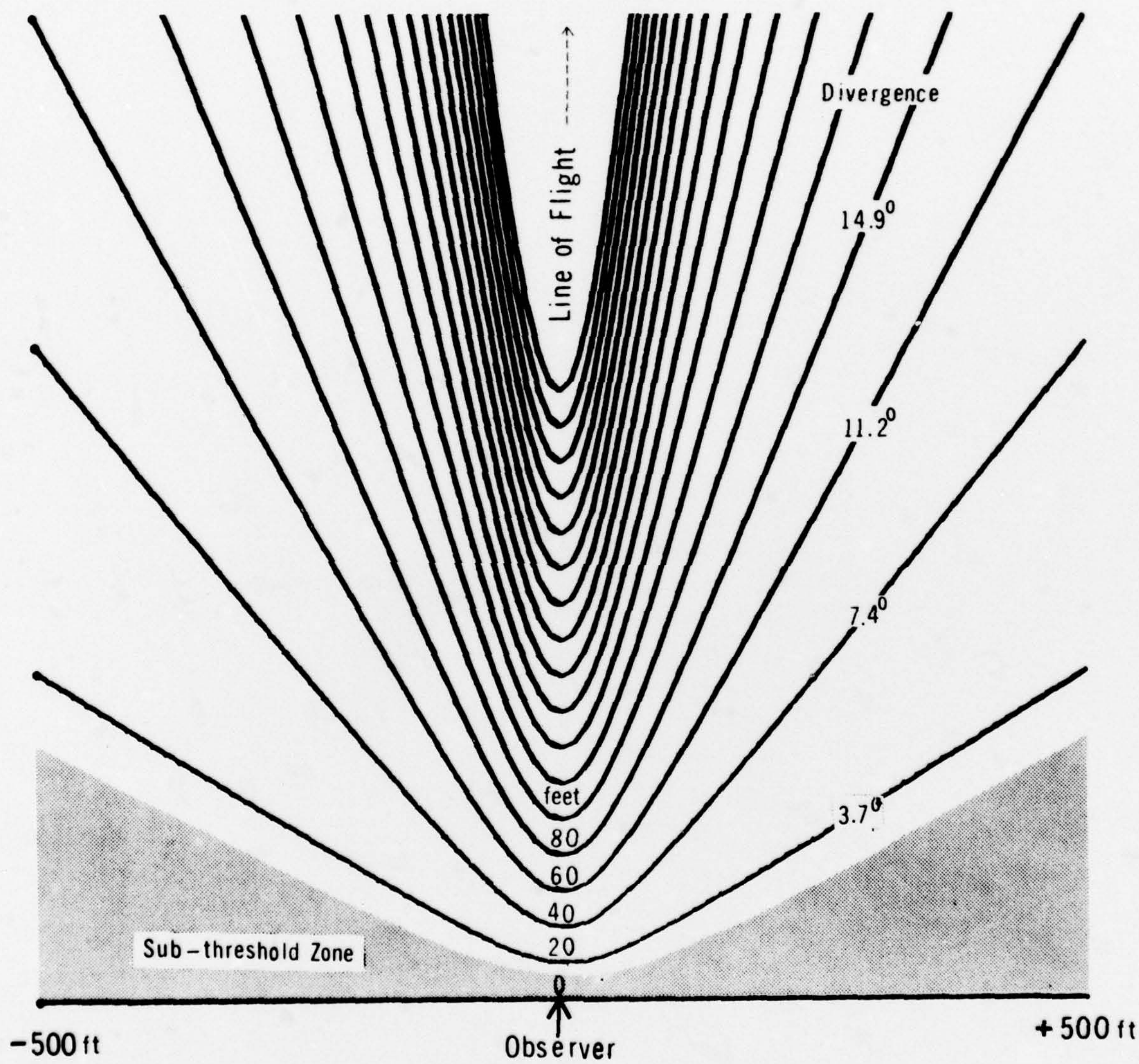


FIGURE 14

Isoverges in the field of view of an observer moving straight and level with his eye 55 ft. above the horizontal plane in the direction indicated by the arrow. *Distances are from the observer* to the vertices of the respective hyperbola and the actual divergence that each isoverge represents is shown. For example, anywhere along the contour labeled "20 ft." *the observer* will see a divergence of 3.7°. All divergences below average foveal threshold as determined by the experiments lie approximately in the shaded zone.